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Randomness analysis in authenticated encryption systems

Master thesis

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Declaration

Hereby I declare, that this paper is my original authorial work, which I have worked out by my own. All sources, references and literature used or excerpted during elaboration of this work are properly cited and listed in complete reference to the due source.

Martin Ukrop

Advisor: RNDr. Petr Švenda, Ph.D.

Acknowledgement

Many thanks to you all.

There would be much less algebra, board gaming, curiosity, drama, experience, functional programmig, geekiness, honesty, inspiration, joy, knowledge, learning, magic, nighttime walks, OpenLabs, puzzle hunts, quiet, respect, surprises, trust, unpredictability, vigilance, Wachumba, xylophone, yummies and zeal in the world for me without you.

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Abstract

This thesis explores the randomness of outputs created by authenticated encryption schemes submitted to the CAESAR competition. Tested scenarios included three different modes of public message numbers. For the assessment, four different software tools were used: three common statistical batteries (NIST STS, Dieharder, TestU01) and a novel genetically inspired framework (EACirc). The obtained results are interpreted in two ways: Firstly, to gain insights into the quality of the proposed CAESAR candidates. Secondly, to compare and contrast the used randomness testing tools. Directions for future research are proposed based on the obtained conclusions.

Keywords

statistical randomness, authenticated encryption, CAESAR, evolutionary algorithms, genetic programming, EACirc, NIST STS, Dieharder, TestU01

Contents

1 Introduction

Nowadays, cryptography interferes with almost every aspect of our lives. Ongoing research of cryptoprimitives is, therefore, essential to ensure they provide the assurances required. The assessment can be done in a multitude of ways – this thesis concentrates on randomness testing. Even though finding patterns in the produced outputs does not prove the design insecure, it significantly hints at its potential weaknesses.

Historically, randomness was assessed primarily by statistical tests. Over time, multiple tests were grouped into suites, such as *Statistical Test Suite* by the National Institute of Standards and Technology (NIST STS) [Nat97b]. However, creating the tests required an enormous amount of human analytical work. Furthermore, the tests were limited to predefined data characteristics manually inspected by the analysts. Recently, other approaches supplementing statistical batteries started to emerge [Š+12; Kam13]. Although they offer potential to use novel and/or unusual data characteristics, it is wise to complement them with results obtained by standard means.

In this thesis, we chose to scrutinize submissions of the ongoing CAESAR competition [CAE13] (*Competition for Authenticated Encryption: Security, Applicability, and Robustness*). The authentication tags produced by all candidates are examined using four different software tools: a novel genetically-inspired framework (EACirc [Š+12]) and three standard statistical batteries (NIST STS [Nat97b], Dieharder [Bro04] and TestU01 [LS07]). The research is a natural continuation of previously published works [Ukr13; Sýs+14].

Following this introduction, in chapter 2, accounts of related work are given. Next, in chapter 3, we summarize the relevant details of the CAESAR competition, its submissions and the procedures necessary to use them. Chapter 4 describes the methodology of the performed experiments, introducing the used tools, their fundamental operating principles and settings. The tests we carried out are reported in chapter 5 along with the interpretation of the measured values. Chapter 6 concludes the thesis by summarizing the main conclusions and proposing directions for the future.

Although the research presented in this thesis was done mostly by myself, plural is used in the thesis text. EACirc and the related research is a result of a wider team[1] at the Centre for Research on Cryptography and Security, Masaryk University, where all problems and ideas are discussed together. Parts primarily done by others are properly attributed when mentioned.

The thesis text was typeset in LaTeX using the *fithesis2* package created by S. Filipčík [Fil09]. The text of this thesis is licensed under a Creative Commons Attribution 4.0 International License.[2] The icons used in the diagrams were taken from *The Noun Project*[3] are in public domain or licensed under Creative Commons Attribution 3.0 United States.[4]

1. The most notable people involved in the creation of this thesis include Petr Švenda, Marek Sýs, Karel Kubíček, Jiří Novotný and Ľubomír Obrátil.
2. Licence details can be found at `https://creativecommons.org/licenses/by/4.0/`.
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2 Previous works

The research presented in this thesis combines several tools and ideas. Its primary goal is to assess the output produced by authenticated encryption systems by trying to find a working distinguisher. The summary of this approach previously applied to other categories of cryptoprimitives as well as other research on authenticated encryption schemes is summarized in section 2.1.

Apart from statistical batteries that are commonly used for randomness assessment, we use a novel genetically inspired framework EACirc. Previous research done using this framework can be found in section 2.3 and the explanation of its principles and settings in section 4.2. EACirc is based on genetic programming [Ban+97] – an evolutionary algorithm-based stochastic methodology inspired by biological evolution to find computer programs that perform a user-defined task. Such methodologies have been used in cryptography before – a summary of the most relevant research can be seen in section 2.2.

2.1 Cryptoprimitives assessment

Numerous works tackled the problem of assessing randomness of outputs from cryptoprimitives before. E. Simion [Sim15] gave a nice and readable overview of statistical requirements for cryptographic primitives and the relevance of statistical testing. Usually, statistical testing with standard batteries of tests is performed. The Ph.D. thesis of K. Jakobsson [Jak14] gives both a good theoretical background and a comparison of commonly available tools for random number testing. Its results are based on assessing a variety of pseudo-random and quantum random number generators.

Cryptographic competitions are often the target of these analyses since the unified function API allows for effortless evaluation of a high number of schemes. M. Turan et al. [TDÇ08] performed a detailed examination of eStream phase 2 candidates (both full and reduced-round) with NIST STS and structural randomness tests, finding six ciphers deviating from expected values. In 2010, Doganaksoy et al. [Dog+10] applied the same battery, but only a subset of tests to SHA-3 candidates with a reduced number of rounds as well as only to their compression functions. 256-bit versions of SHA-3 finalists were then subjected to statistical tests using a GPU-accelerated evaluation by A. Kaminsky [Kam12] detecting some deviations in all but the *Grøstl* algorithm.

CryptoStat [Kam13] constitutes a different view of the problem, using the Bayesian model selection to evaluate the randomness of block ciphers and MACs.

As CAESAR (*Competition for Authenticated Encryption: Security, Applicability, and Robustness*) [CAE13] is an on-going initiative with many submissions (details in chapter 3), there are still not many publications thoroughly examining the security of all the proposed algorithms. F. Abed et al. [AFL14] give an excellent overview of the candidates along with a classification with regard to their core primitives. K. Hakju and K. Kwangjo [HK14] discuss the features of authenticated encryption and predict the essential characteristics of the submissions to survive the CAESAR competition.

No deeper competition-wide comparison has been done so far – more detailed analysis was performed only on a per-candidate basis. For example, R. Ankele in his Ph.D. thesis [Ank15] analyses the *COPA* authenticated encryption composition scheme used in several CAESAR candidates. M. Nandi in his 2014 paper [Nan14] demonstrates a forging attack on *COBRA* and *POET* designs.

2.2 Genetic algorithms in cryptography

Genetic algorithms were previously applied also in cryptography to some extent. A comprehensive review of the usage up to the year 2004 can be found in B. Delman's Ph.D. thesis [Del04]. A more recent review is provided in the Ph.D. thesis of S. Picek [Pic15].

For testing randomness of outputs from cryptoprimitives using genetic algorithms, *Tiny Encryption Algorithm* (TEA) is frequently used. TEA, a simple block cipher designed by D. Wheeler and R. Needham [WN95], constitutes a useful benchmark due to its simple design with multiple repeated rounds.

Starting in 2002 with a paper by J. Hernández et al. [Her+02], statistically significant deviances were found for TEA limited to 1 and 2 rounds. A fixed bitmask with a high Hamming weight evolved by genetic algorithms was applied both to the cipher input data and key. The expected distribution of bit patterns of 10 least significant bits of ciphertexts were then evaluated with a χ^2 test. Two years later, using the same approach, a similar team published improved results [HI04] detecting deviances for 3 and 4 rounds as well. Subsequent work by W. Hu [Hu10] in 2010 improves an earlier attack with quantum-inspired genetic algorithms, succeeding for TEA reduced for 5 rounds. However, up to the publication of this thesis at the beginning of 2016, no distinguisher for a higher number of rounds was found.

Using a different technique, E. Ma and Ch. Obimbo [MO11] realized an attack on TEA limited to 1 round in 2011. They utilized genetic algorithms and harmony search for the derivation of degenerated keys instead of detection of statistical deviances of output.

2.3 EACirc framework

EACirc [Š+12] is also based on the techniques of genetic programming but constructs a different type of results when compared to the research presented in section 2.2. Instead of bitmasks, it searches for a program (in the form of a software circuit) working as a randomness distinguisher. Furthermore, EACirc tries to find defects in outputs of cryptoprimitives (such as dependent or biased bits) without directly manipulating plaintexts for the cipher (unlike the case with the evolved bitmasks).

Previously, we used the framework for assessing the randomness of output produced by the round-limited eSTREAM and SHA-3 candidates [Ukr13; ŠUM13; ŠUM14]. To improve the results and increase the number of successfully distinguished rounds, an improved evaluator module based on χ^2-test was developed [Sýs+14]. Although still falling behind in some cases, this improvement enabled us to surpass NIST STS in a few instances.

To be able to compare EACirc's capabilities with other used methodologies, round-limited TEA was inspected as well [Kub+16]. As previously, our achievements were comparable to the standard statistical batteries, being able to distinguish TEA with 4 or fewer rounds.

During the research, a need arose for supporting tools speeding up and simplifying the performed experiments. On the one hand, implementing crucial parts of the framework in nVidia CUDA suitable for GPU acceleration [Nov15] enabled us to have significantly more test vectors. On the other hand, automating the creation, distribution and evaluation of multiple jobs in a suitable environment with the *Oneclick* tool [Obr15] made quick benchmarking possible and convenient.

3 Authenticated encryption

A cryptosystem for authenticated encryption simultaneously provides confidentiality, integrity, and authenticity assurances on data – decryption is combined in a single step with integrity verification. Authenticated ciphers are often built as various combinations of block ciphers, stream ciphers, message authentication codes, and hash functions. There are many examples commonly used today, such as the *Offset codebook mode* (OCB) [Rog+01] or *Galois/counter mode* (GCM) [MV04] based on block ciphers.

Combining confidentiality and integrity assurances into a single scheme has tremendous advantages as combining a confidentiality mode with an authentication mode could be error prone and difficult[1]. Therefore, following a long tradition of cryptography competitions, CAESAR [CAE13] aims to create a portfolio of authenticated encryption systems intended for wide public adoption.

The object of this thesis is to assess several authenticated encryption schemes with regard to the randomness of produced outputs. To ease the testing of a multitude of systems, we decided to restrict ourselves to just to the CAESAR submissions. This allows us to take advantage of the unified API prescribed by the competition.

The rest of the chapter contains details on the ciphers tested. In section 3.1, CAESAR competition details are given along with general requirements and statistics of all its submissions. In section 3.2, we describe the set of tested functions and their necessary modifications.

3.1 CAESAR competition

CAESAR (*Competition for Authenticated Encryption: Security, Applicability, and Robustness*) [CAE13] is an effort to identify a portfolio of authenticated ciphers that are suitable for widespread adoption and offer an advantage over AES used in *Galois/counter mode* [MV04].

The contest builds on a strong tradition of focused cryptography competitions believed to have boosted the cryptographic research and enhanced the understanding of the underlying primitives. The first and most well-known was an open competition for a new *Advanced Encryption Standard* [Nat97a] held in 1997 by the United States National Institute of Standards and Technology (NIST). In 2004, ECRYPT (*Network of Excellence* funded by the European Union) announced eSTREAM, the *ECRYPT Stream Cipher Project* [Eur05] calling for a new stream ciphers suitable for widespread adoption. In 2007, NIST announced an open competition for a new hash standard, SHA-3 [Nat07]. Most recently (2013) the crypto community's efforts were focused on password processing in the *Password Hashing Competition* [PHC13].

1. „It is very easy to accidentally combine secure encryption schemes with secure MACs and still get insecure authenticated encryption schemes.“ [KVW03]

The final deadline for CAESAR submissions was on March 15th, 2014. All 56 proposals were published for detailed evaluation and wider scrutiny. The organizing committee expects three regular rounds and one final before announcing the final portfolio. The authors of the original submissions are allowed to perform further tweaks in the subsequent rounds. The tentative submission deadlines are in mid-2015, the first quarter of 2016 and the beginning of 2017 respectively.

All submissions should be usable in both software and hardware version. Although the first round requires only software implementations, each candidate selected for the second round will also be required to include a reference hardware design. Submitters are free to choose the intellectual property status of their designs (i.e. patented submissions are allowed), but the committee states that patenting a cipher is likely to be considered as a downside.

3.1.1 Candidates requirements

Authenticated ciphers (as required by the CAESAR submission call) take five byte-string inputs and one byte-string output with different security purposes. The inputs are as follows:

- **Key**
  A mandatory byte-string with length fixed to an arbitrary number (nevertheless, it is recommended to support 80, 128 and 256-bit keys).
- **Plaintext**
  A mandatory variable-length input. Designers are permitted to specify the maximum length (but not smaller than 65 536 bytes). The proposed cryptosystem should ensure both integrity and confidentiality for the plaintext.
- **Associated data**
  A mandatory variable-length input, the integrity of which must be preserved by the cipher. The maximum length may be set, but it must not be less than 65 536 bytes.
- **Public message number**
  An optional fixed-length field, the integrity of which must be preserved. Designers may impose single-use limits, see discussion for the secret message number.
- **Secret message number**
  An optional byte-string with fixed length. Both integrity and confidentiality must be retained. The call advises that existing solutions often avoid using secret message numbers. Candidates are expected to maintain security regardless of the way the users choose message numbers. However, ciphers are permitted to lose all security if a single (secret message number, public message number)-pair is used for two encryptions with the same key.

All submissions must accept all byte-strings meeting the specified lengths. Any length limits must be thoroughly justified in the submitted documentation. It is permitted to leak the plaintext length via the ciphertext length (e.g. by having the ciphertext and plaintext length difference be constant).

Each submission specifies a family of authenticated ciphers. Family members differ only in parameters (e.g. key length, the number of „rounds“). The list of recommended parameter sets must be prioritized and have at most 10 items with justification for each recommendation. The presented documentation should include the authors, full specification, security goals for each parameter set, security analysis, feature list, design rationale and intellectual property status.

All candidates are required to be self-contained (i.e. the documentation should include all information necessary to implement the cipher from scratch), except for AES encryption and decryption utilities with the key lengths of 128, 192 and 256 bits.

3.1.2 Submissions

There were 56 different designs submitted to the first round. Taking into account all possible parameter sets, this amounts to 172 independent schemes. Till the announcement of the second-round candidates, 9 designs were withdrawn by their authors. On July 7th, 2015, 29 designs were chosen for the second round.

Each first-round candidate is accompanied by a portable reference software implementation. This enables extensive public scrutiny of the design and verification of subsequent implementations. This implementation must cover all recommended parameter sets, and must compute exactly the function specified in the submission. All submissions are available in eBACS, the *ECRYPT Benchmarking of Cryptographic Systems* [Vir08].

3.2 Tested ciphers

Our goal was to test as many authenticated encryption schemes as possible. Using CAESAR candidates enabled us to test many designs and many configurations automatically due to the shared API. All the candidate codes were taken from the SUPERCOP repository managed by eBACS [Vir08].

In the end, there were 168 different ciphers tested in all performed experiments. From 172 submitted independent schemes (56 designs with different parameter sets), 6 were not tested. Firstly, we could not get the *AVALANCHE* candidates working properly (segmentation fault while running). Secondly, *Julius* did not compile due to problems with the inclusion of the external AES routines provider. Thirdly, *POLAWIS* seemed not to have followed the prescribed API. Lastly, the implementation of *PAES* is probably faulty, since it did not pass our encrypt-decrypt sanity test. We might have been able to fix most of these cases, but doing so would require extensive interventions in the code increasing the possibility of error. Apart from the submitted candidates, we tested 2 versions of *AES/GCM* referenced by the CAESAR committee as a design baseline.

On the one hand, some modifications of the source code were needed to compile the ciphers successfully within the EACirc framework. On the other hand, any changes to the implementations increased the possibility of error potentially causing meaningless results. Therefore, an highly cautious approach was taken: All used ciphers were accompanied by a

metadata file and the necessary changes to the source code were thoroughly tracked. The basic metadata file consists of the following:

- Unique identifier of the candidate, the submission family it belongs to and its authors.
- The used implementation type and version along with the exact URL and date of download.
- The summary of necessary changes performed in the scheme's codebase.

Apart from this file, any change in the code is prefixed with a commentary line starting with a keyword `CHANGE` and a reason for the adjustment (to ease the subsequent localization of changes). Furthermore, in the case of nontrivial modifications, the commentary is followed by the commented original version of the code section.

Due to the high volume of the tested ciphers, the basic adjustments were done automatically using custom-made scripts. This made the subsequent manual inspection of all source files a must. In the process, the following modifications were made (not exhaustive):

- **File renaming and creation of the folder structure**
  Many designers shared the names of the main source files (such as `encrypt.c`). To uniquely identify each source file both for comprehension and the ease of compilation, all files were prefixed by the unique name of the design and its parameter set. The codebase was then hierarchically organized to allow simple work with cipher families.
- **Conversion to C++, header includes resolution**
  To simplify and unify the linking process, all source files written in C were treated as C++ (and therefore renamed to have a `.cpp` suffix). To allow for the file renaming in this and the previous point, all the header file inclusion had to be appropriately adjusted.
- **Namespacing, object interface creation**
  Since all the ciphers were defining the same functions (prescribed by the competition API), the individual implementations needed to be separated. For this, we used C++ namespaces, enclosing each cipher into a distinct virtual space. During the computation, the implementations are accessed via a virtual CAESAR cipher interface with a generated object for each candidate.
- **Dependency resolution**
  As the submission requirements permit the usage of AES routines without implementation, several designs relied on external libraries such as *OpenSSL* [Ope98]. In other cases, the ciphers depended on other routines available in the SUPERCOP repository [Vir08]. These were separated out and provided to all the candidates in question.
- **Preparation for round limitation**
  To aid the foreseeable future work, an extra variable was added to each namespace via the generated object interface. If realized, it will be used to weaken the cipher design by limiting the number of its internal rounds that would enable us to analyze its security properties more precisely and have a finer comparison of the used tools.

Although it is not used for the presented work at all, the modifications had been done since they imposed a negligible overhead during the automatized mass adjustment phase.

- **Compiler issues resolution**
  During experiments, EACirc is run on both Windows and Linux. Thus, the framework is kept compilable using both *GNU Compiler Collection* and *Microsoft Visual Studio C++ Compiler*. Several changes were, therefore, necessary to ensure a clean build in both these environments, as not all the submissions were perfectly portable. These included, for instance, swapping the variable length arrays allocations for standard dynamic memory management, consolidating data types or enforcing a stricter object management using static casts.
- **Other specific issues**
  For some designs, other minor issues needed to be resolved. To name at least one, *CLOC* and *SILC* candidates lacked accompanying calls for dynamic memory cleanup causing memory leaks. These had to be added since a repeated call for the encryption routine during the generation of the stream intended for statistical batteries (see chapter 5 for details on performed experiments) caused a massive memory consumption increase.

4 Experiment methodology

The main goal of this thesis is to assess randomness of outputs produced by different authenticated encryption schemes. For the ease of implementation, only submissions for the recent CAESAR competition were evaluated (more information on the competition can be found in chapter 3).

The high-level overview of the assessment procedure is summarized below as well as in figure 4.1. The data stream produced by the particular cipher is independently assessed by several statistical batteries. The usage details, as well as used settings, are described in section 4.1. Furthermore, a novel genetically inspired framework EACirc is used to replicate the assessment and provide a different approach to the problem solution. The overview of EACirc, its settings and interpretation of its results is given in section 4.2. The details on CAESAR candidates settings, numerical results and their interpretation can be found in chapter 5. Section 4.3 provides reference experiments for all the used tools.

4.1 Statistical batteries

Evaluating the quality of randomness of a given data stream is a difficult task. In practice, randomness assessment heavily relies on empirical tests of randomness. Each test examines the data from a particular point of view, testing certain statistical features (e.g. the ratio of zeros to ones or the frequency of ones in m-bit blocks). The majority of randomness tests are based on statistical hypothesis testing. The observed characteristics of data are compared with the expected test statistic precomputed for infinite random sequences.

However, even a good random number generator sometimes produces sequences (for instance a sequence of many consecutive ones) with characteristics significantly different from the values expected in tests. Therefore, we are unable to distinguish with certainty whether a given sequence with „bad“ characteristics was produced by a defective generator or by a sound generator in a rare case. Thus, the randomness is expressed as a probability, usually in terms of p-values. To draw conclusions, we choose a significance level α (the type I error) indicating the likelihood of error when rejecting the randomness of a given sequence.

Since statistical randomness can be tested from many points of view, tests are usually grouped into testing suites to provide more comprehensive randomness analysis. One of the first compact sets of randomness tests was the *Diehard Battery of Tests of Randomness* by G. Marsaglia [Mar95]. Soon after, the *Statistical Test Suite* by the National Institute of Standards and Technology (NIST STS) [Nat97b] and the theoretical summary by D. Knuth [Knu97] followed. The NIST STS has a special importance since it was published as a NIST standard and is still used for the preparation of many formal certifications or approvals (for example for selecting AES). As these suites ceased to be maintained and improved, new efforts for a modular and extensible testing frameworks arose. These included Dieharder [Bro04], TestU01 [LS07] and ENT [Wal08] to name just a few.

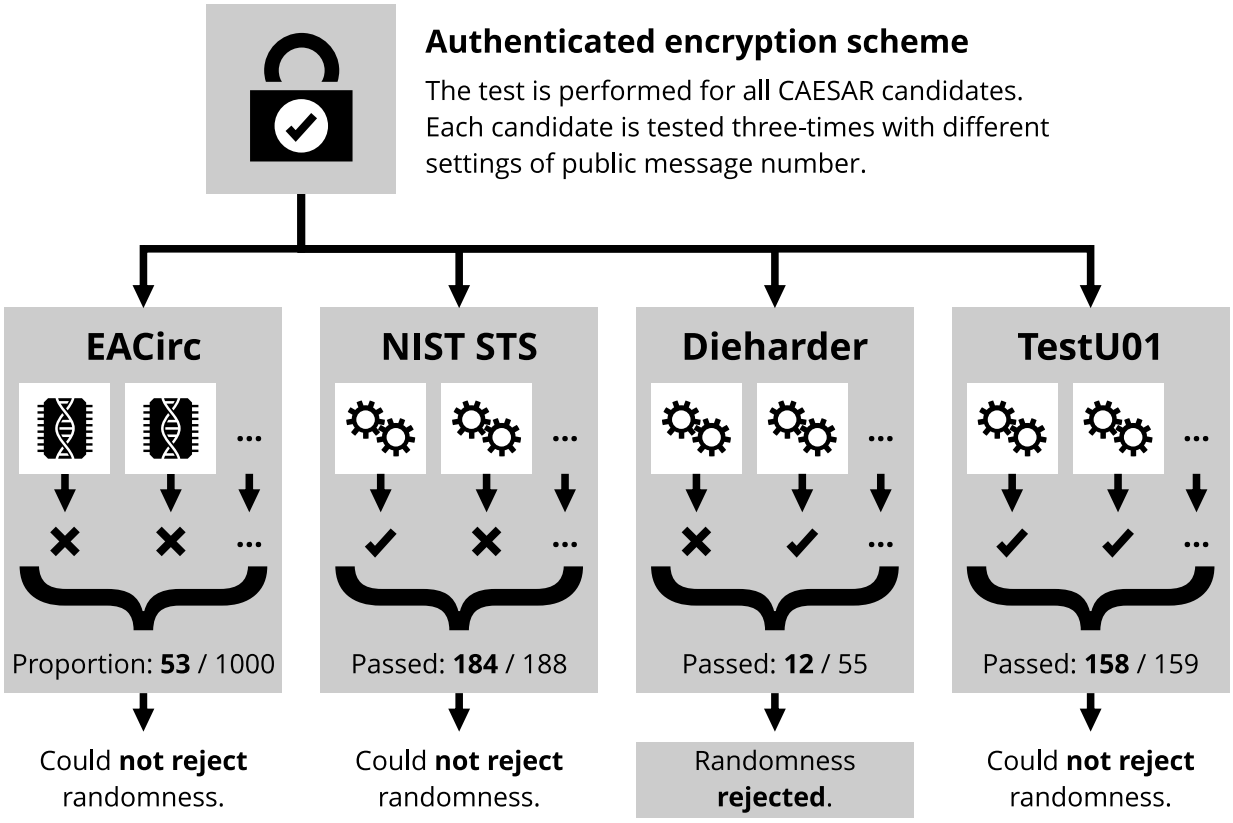


Figure 4.1: High-level overview of the performed experiments. Details about the used tools can be found in chapter 4. Interpretation of the numerical results are summarized in section 5.2.

For the ease of usage (yet still keeping a wider variety of suites) we tested out sequences with the following three statistical testing suites: NIST STS (older, yet still commonly used and a valid NIST standard), Dieharder (modern framework reimplementing other suites as well as adding brand new tests) and TestU01 (another modular framework implementing many tests).

Although the p-value of a randomness test focusing on a single characteristic has a clear statistical interpretation, the interpretation of results produced by testing suites is somewhat problematic. We need to determine what number of failed tests allows us to reject randomness of the assessed sequence while respecting the chosen significance level. For this, we use the methods proposed by M. Sýs et al. [Sýs+15]. The resulting threshold for all batteries can be found in the following subsections.

For all experiments, we chose the significance level of $\alpha = 1\%$. This keeps the type I. error (false positives) reasonably low while preventing the type II. error (false negatives) to reach too high values.

4.1.1 NIST STS

A *Statistical Test Suite for Random and Pseudorandom Number Generators for Cryptographic Applications* [Nat97b] is a battery of statistical tests implemented by National Institute of Standards and Technology. It consists of 15 independent tests. Five of these tests (the cumulative sums test, non-overlapping template matching test, serial test, random excursions test and random excursions variant test) are performed in more variants. These can be seen as separate sub-tests, the whole battery, therefore, amounting to 188 tests altogether. It should be noted that some tests (runs, random excursions and random excursions variant) are not always applicable. These tests are applied only if the sequence meets certain criteria (frequency test passes, the number of cycles is greater than 500). Excluding these, there are 162 tests altogether.

We used NIST STS version 2.1.1. When running the tests, we retained the default parameters (block lengths) for all tests. The confidence level was also left unchanged at the value of $\alpha = 1\%$. To comply with the minimal required stream length for individual tests [Ruk+00], we tested 100 independent 1 000 000 bit long sequences for each candidate. In summary, NIST STS used about 12 MiB of input data for each test. For more details on the assessed data stream, see section 5.1.

Regarding the interpretation of a single test, NIST STS adopted the following methods:

- **Proportion of sequences passing the test**
  The relative number of sequences passing the test should lie within a pre-computed interval (the width of the interval depends on the chosen significance level).
- **The uniformity of resulting p-values**
  p-values computed for random sequences should be uniformly distributed on the interval $[0, 1]$. Uniformity of p-values can be tested using a second-level statistical tests.

For us, the test is considered failed if either of these two methods label the test as failed. We conclude the assessed data stream was not random (i.e. we reject the randomness hypothesis on the significance level of $\alpha = 1\%$) if at least 7 tests fail. This interpretation is based on the research by M. Sýs et al. [Sýs+15].

The main point of the cited paper can be summarized as follows: The chosen significance level (in our case $\alpha = 1\%$) is the type I error for a single test. So assuming the null hypothesis holds, and the tested data is random, each test has $1 - \alpha = 99\%$ chance of passing. That means the probability of all 188 tests passing is $0.99^{188} \approx 0.151 = 15.1\%$ that is far from the chosen significance level. To achieve the required type I error of 1%, we must allow some tests to fail. Computing the exact probabilities we get to the chosen significance level for at most 6 failing tests:

$$\sum_{i=0}^{6} \binom{i}{188} 0.99^{188-i}\, 0.01^{i} \approx 0.997 = 99.7\% > 1 - \alpha$$

This, however, assumes the independence of all tests in the battery. M. Sýs et al. therefore confronted the expected distribution with the distribution for a huge amount of quantum

random data. For NIST STS, the difference is small. Nevertheless, the assumption probably is more violated for other test batteries, as can be seen in our reference experiments (section 4.3).

4.1.2 Dieharder

This testing suite was developed by R. G. Brown at the Duke University [Bro04]. Its main aim is to make the process of testing randomness of bit streams easy while it is still possible for researchers to control tests on a low level. The suite is not just a descendant of Diehard [Mar95], although it mainly includes tests from this suite in an enhanced way. Tests from NIST STS are being incorporated into the battery as well as entirely new tests developed by its authors and other users. This tool features many improvements over Diehard such as full extensibility, simple user interface or open source code.

The complete suite has 26 different tests (18 based on the original Diehard tests, 3 reimplemented from NIST STS and 5 from other sources) as of 2015. Two tests out of these were not run – the Diehard sums test (since its usage is strongly discouraged by the authors) and the Marsaglia and Tsang GCD test (because it requires impractically long input streams for our scenario). Excluding these two and taking into account all the variants, there are 55 tests altogether.

We used Dieharder version 3.31.1. The two parametrizable tests were configured with recommended values (12-tuples for RGB bit distribution test, 8 000 points in 2 dimensions for RGB generalized minimum distance test). The default significance level for Dieharder is 0.000 1% (strong reject) and 0.5% (weak reject). In order to ease the comparison with the other used batteries, we decided to reset these to the value of 1%. Although this causes a loss of information (which rejects were weak and which were strong), we prefer such setting to improve the comprehension of results presented alongside the outcomes from other tools.

The length of the input stream processed by Dieharder varies from test to test. The humblest required about 48 kiB, while the greediest one of the run tests takes about 9.2 MiB. To ensure the best possible comparability with the other test suites, we again analysed 100 independent samples of the input. In summary, Dieharder tests used between 4.7 MiB and 916 MiB of input data (depending on the particular test). For more details on the assessed data stream, see section 5.1.

The interpretation of the battery results is similar to the case of NIST STS (see section 4.1.1). The situation is slightly simpler as there is only a single pass/fail output for each test (Dieharder does not assess the proportion of the sequences on which the test passed, only the uniformity of the resulting p-values). Using the same methodology as before, we expect the assessed data stream is not random (i.e. we reject the randomness hypothesis on the significance level of $\alpha = 1\%$) if at least 4 tests fail. However, tests in Dieharder does not seem to be completely independent of each other, see results in section 4.3.

4.1.3 TestU01

TestU01 is a library for empirical testing of random number generators. It was developed at Université de Montréal mainly by Pierre L'Ecuyer [LS07]. The library implements several types of random number generators in a generic form, as well as many specific generators proposed in the literature or found in widely-used software. It provides general implementations of the classical statistical tests for random number generators, as well as several others proposed in the literature, and some original ones.

It implements various sub-batteries intended for different purposes and has a different set of tests. The most relevant sub-batteries are Rabbit, Alphabit and BlockAlphabit. These are intended for testing finite binary sequences. Rabbit and Alphabit apply 38 and 17 different statistical tests respectively. BlockAlphabit applies the Alphabit battery repeatedly after reordering the bits by blocks of different sizes (2, 4, 8, 16 and 32 bits). Including all the applicable sub-tests there are 159 tests. We used TestU01 version 1.2.3.

The length of the input stream taken by TestU01 can be set arbitrarily. To have an amount of data comparable with the other used batteries, we chose to process 2^{30} bits for each test. In summary, TestU01 thus used about 128 MiB of input data for each test. For more details on the assessed data stream, see section 5.1.

In order to be as close as possible to the other statistical testing suites, we changed the default value of the significance level (0.1%) to the common level of $\alpha = 1\%$. The interpretation of the battery results is similar to the previous cases (see section 4.1.1, section 4.1.2). Using the same methodology as before, we expect the assessed data stream is not random (i.e. we reject the randomness hypothesis on the significance level of $\alpha = 1\%$) if at least 6 tests fail. However, tests in TestU01 are not independent of each other. The interdependence could have been foreseen, considering the principle of BlockAlphabit. For more details see section 4.3.

4.2 EACirc

In this section, we try to describe the ideas and workings of EACirc [Š+12], a novel framework for automatically generating statistical randomness tests. Compared to the standard (manual) way of test creation (as was the case with all the tests used in statistical batteries), our approach has a couple of advantages:

- no prior knowledge of statistical properties of random data is needed;
- test creation does not require excessive human analytical labour;
- tests are dynamically adapting to the tested data;
- atypical and/or yet unknown input data properties may be used to distinguish them from the reference random data.

The main idea is to use supervised learning techniques based on evolutionary algorithms to design and further optimize a successful distinguisher – a test determining whether its input comes from a truly random source or not. The distinguisher will be represented as a

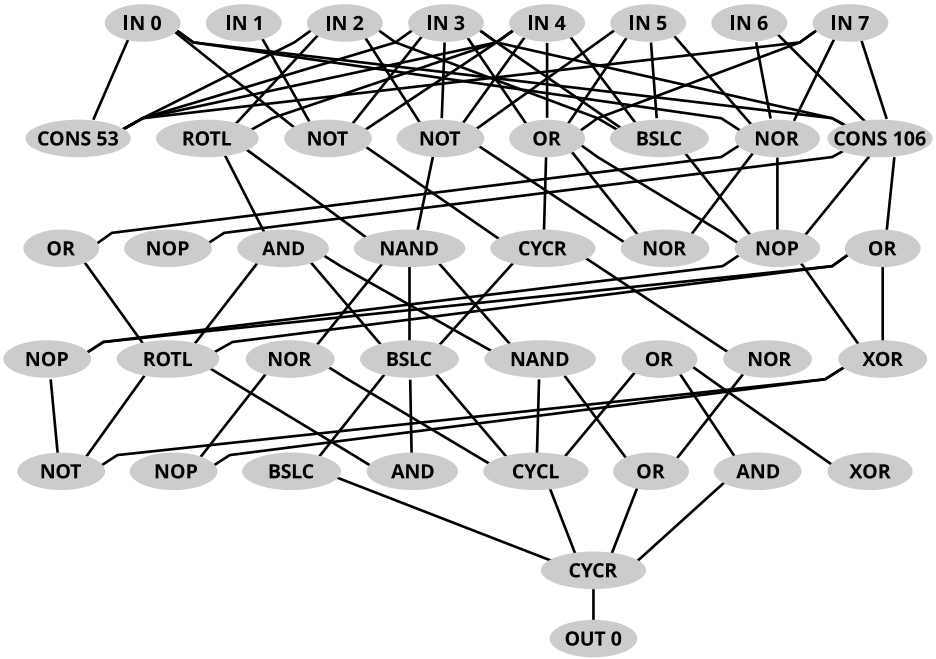


Figure 4.2: Example of software-emulated circuit as used within EACirc in our experiments.

hardware-like circuit consisting of simple interconnected functions. The evolution will use the principles of genetic programming.

The framework was previously used for assessing randomness of outputs produced by stream ciphers and hash functions [ŠUM13; Sýs+14]. Although some parts of the design have since evolved, most of this section is based on the detailed description published previously [Ukr13; ŠUM14]. The overview of further research based on this tool can be found in section 2.3.

4.2.1 Workflow

EACirc works with a notion of a *circuit* – a software representation of a hardware-like circuit with nodes (responsible for computation of simple functions, e.g. AND, OR) and connectors (linking node inputs and outputs). A circuit is formed by several layers of such nodes. A node may be connected to any number of nodes from the previous layer – to all, only some of them or none at all. A simple circuit overview can be seen in figure 4.2. Contrary to real single-layer hardware circuits, connectors may also cross each other.

Circuit usage is versatile – from Boolean circuits where functions computed in nodes are limited to logical operators to artificial neural networks where nodes compute the weighted sum of the inputs. Besides studying complexity problems, these circuits were used in various applications such as the design of efficient image filters. Circuit evaluation can be performed by a software emulator or directly in hardware when FPGAs are used.

EACirc's main goal is to find a circuit that will reveal an unwanted defect in the inspected cryptographic function. For example, if a circuit can correctly predict the n^{th} bit of a stream cipher output just by observing the previous $(n-1)$ bits, then this circuit serves as a next-bit predictor [Yao82], breaking the security of the given stream cipher. When a circuit can distinguish the output of the tested function from a truly random sequence, it serves as a random distinguisher [EHJ07] providing a warning sign of function weakness. Note that a circuit does not have to provide correct answers for all inputs – it is sufficient if a correct answer is provided with a probability significantly higher than random guessing.

The greatest challenge is the precise circuit design. It can be laid out by an experienced human analyst (representing a known test, e.g. monobit test) or created and further optimized automatically. We use the latter approach and combine a software circuit evaluated on a CPU/GPU with evolutionary algorithms. The whole process of circuit design, as also depicted in figure 4.3, is as follows:

0. A set of circuits (possible solutions) is initialized by randomly selecting both functions in nodes and connectors in between them. Note that such a random circuit will, most probably, not provide any meaningful output for given inputs and can even have disconnected layers.
1. If necessary, new test vectors used for success evaluation are generated. Half of these is taken from the pseudorandom stream of assessed data (outputs of authenticated encryption schemes in our case) while the other half constitutes a reference sample generated by a truly random generator.
2. Every individual (circuit) in the population is evaluated on all test inputs. The fitness function assigns each circuit a rating based on the obtained outputs (e.g. what fraction of inputs were correctly recognized as being outputs of a stream cipher rather than completely random sequences, see section 4.2.2 for details).
3. What follows is the survival phase, in which worse individuals (the ones with lower fitness value) are removed from the process.
4. Based on the evaluation provided by the fitness function, a potentially improved population is generated from the existing individuals by mutation and sexual crossover. Every individual (circuit) may be changed by altering operations computed in nodes and/or adding/removing connectors between nodes in subsequent layers.
5. The process is repeated from step 2. Usually, hundreds of thousands or more repeats are necessary until the desired success rate of the distinguisher is achieved.

4.2.2 Implementation and settings

EACirc can be configured in many different ways. The most important factors are inner workings of the used genetic operators (initializer, fitness assessment, mutation, crossover). For the genetic programming routines, we used the GAlib genetic algorithm package [Wal95], written by Matthew Wall at the Massachusetts Institute of Technology. However, as our individuals are in a form of software circuits, we had to implement the genetic operators ourselves. The initializer generates the initial circuits at random. The mutator changes

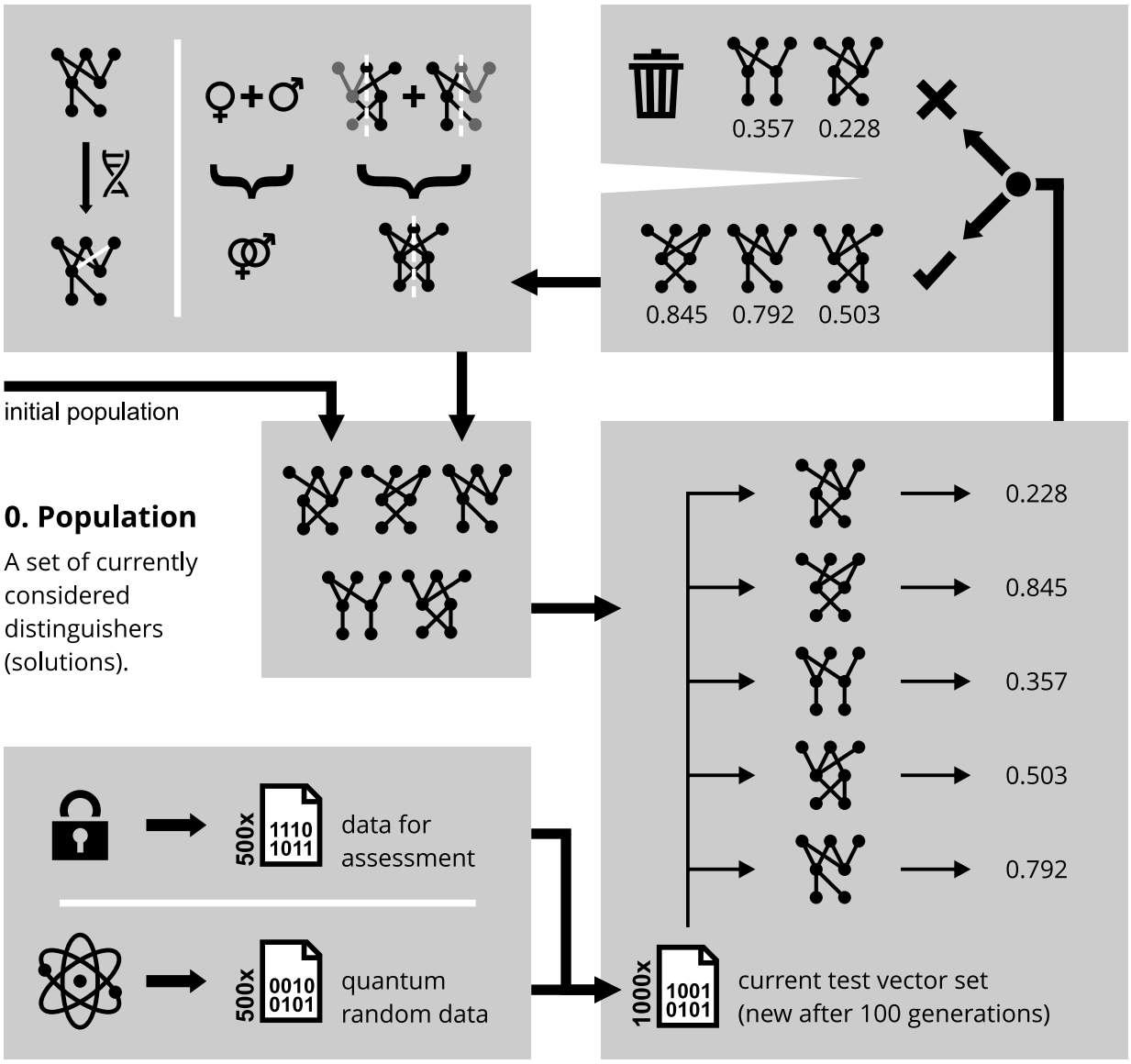


Figure 4.3: A simplified work-flow of the genetic processes in EACirc. The evolution cycle repeats many times. The fitness data from all generations is later analyzed to assess the success of the particular EACirc run.

every connector and every node with a small (but non-zero) probability. The crossover is performed by cutting 2 parent circuits vertically in two parts and joining a part of each parent to create the offspring. For more details, consult the project codebase [Š+12].

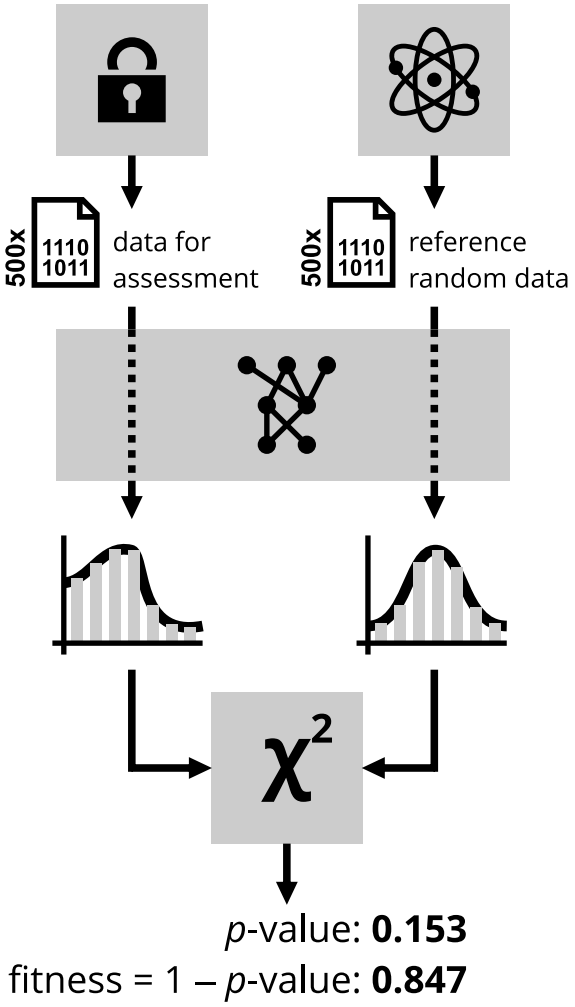
The crucial operator turned out to be the fitness function. Previously [Ukr13; ŠUM13], we used the proportion of correctly identified test vectors (random vs. non-random) as the fitness measure. This prooved insufficient, so the assessment was improved [Sýs+14] as demonstrated in figure 4.4. The idea was to take into account the entire distribution of the circuit outputs in the form of a histogram. For example, if the circuit output is a single byte, the observed distribution of its 256 possible values produced by processing all pseudorandom (i.e. cipher-produced) test vectors was to be compared with the expected distribution using a standard χ^2 test. We approximated the expected distribution by processing the same number of truly random reference data. To solve problems occurring from an inaccurate approximation of expected frequencies, obtained and expected frequencies can be compared using a two-sample test. In our approach, we use the two-sample χ^2 test [Nat93] since the distribution of test statistic values for two-sample χ^2 tests is also the χ^2 distribution. The resulting p-value (expressing the divergence of the distributions produced by truly random and pseudorandom data) is then used as the fitness measure[1] for the circuit's distinguishing capabilities.

In all experiments presented in this thesis, we used the following settings:

- In each computation, 30 000 generations were evolved.
- Each test vector set consisted of 1 000 bitstreams, half of which was produced by the assessed cryptoprimitive while the other reference half was taken from a truly random data source. The test set was renewed in every 100$^{\text{th}}$ generation.
- The generation consisted only of a single individual. Although more individuals may increase the success rate and convergence speed towards a well-performing distinguisher, larger populations also cause problems with the interpretation of results (details in section 4.2.3). Therefore, the crossover operator was disabled for now. For each generation, a single new circuit was generated by mutation and the better of the two was passed into the subsequent evolution – an approach similar to hill-climbing heuristics.
- The circuit nodes operate on bytes. The functions applicable are the basic byte manipulation functions (AND, NAND, OR, XOR, NOR, NOT, left and right shifts and rotations, identity, constant function and function selecting only some bits of the input).
- The evolved circuits are 5 layers with 8 nodes in each intermediate layer. The input layer size is of variable width (details in section 5.1); the output layer is a single byte. The inspected output distribution has 8 categories produced by taking the 3 right-most bits of the output byte.

Unfortunately, there are too many variables in the experiments to list the complete settings

1. To be precise, the fitness value is $(1 - p\text{-value})$, since more successful individuals (divergent histograms, low p-values) need to have a higher fitness value than less successful ones (similar histograms, higher p-values).



Data sources

Testing data come from two sources:
1) Data produced by the tested cryptoprimitive.
2) Reference data from a random generator.

Test vector set

We sample equal amounts of both types of data.

Circuit evaluation

All test vectors are fed into the evaluated circuit. Outputs for both input types are recorded.

Circuit output histograms

A histogram (frequency of particular byte values) is created from outputs for each input type.

Output histogram comparison

The similarity of produced histograms is computed using two-sample χ^2-test.

Final fitness of the circuit

The similarity test outputs a *p*-value in [0,1]. This directly determines the circuit fitness.

Figure 4.4: The summary of fitness computation in EACirc. Each circuit in each generation is evaluated in this way to assign it a fitness value.

here. Since the experiments are based on previously published works, for detailed settings the reader should refer to papers mentioned in section 2.3 (most notably [ŠUM14]) or to the data logs in the attachment.

The used settings cause EACirc to process approximately 2.24 MiB of data produced by the tested cryptoprimitive for a single EACirc run assuming 16-byte long test vectors (for details about other used test vector lenghts, refer to chapter 5). This amounts to about 2.24 GiB of data for a single experiment. See figure 4.5 to see the reasoning behind this number.

The quality of the reference random data is crucial for the good approximation of the expected frequencies and therefore for the entire fitness assessment. We used a stream of 1.2 GiB obtained from the *High Bit Rate Quantum Random Number Generator Service* [Nan10]. It is a joint research effort of PicoQuant GmbH and the Nano-Optics groups at the Department of Physics of Humboldt University providing random bitstreams based on the quantum randomness of photon arrival times.

$$\Sigma = 1\,000\ \frac{\text{runs}}{\text{experiment}} \cdot \left(\frac{30\,000 \frac{\text{generations}}{\text{run}}}{100\ \frac{\text{generations}}{\text{test set}}} \cdot \frac{1}{2} \cdot 1\,000\ \frac{\text{vectors}}{\text{test set}} \cdot 16\ \frac{\text{bytes}}{\text{vector}} \right) \approx 2,24\,\text{GiB}$$

Figure 4.5: The amount of data analyzed by EACirc for a single experiment assuming the test vectors of 16 bytes.

To leverage the massive computing, the individual evaluation was parallelized [Nov15] using nVidia CUDA. The computations were run in a highly distributed fashion on the computers of the Centre for Research on Cryptography and Security at Masaryk University and the National Grid Infrastructure operated by MetaCentrum [Tea15]. The job management was automated with the Oneclick tool [Obr15] to allow for easy replication and experiment settings improvement.

4.2.3 Results interpretation

To interpret the results of a single EACirc run, we inspect the fitness of individual partial solutions (circuits) in the generations just after the test set change. That is, we are interested in fitness values produced on test vectors never-before-seen by the particular circuit. This mitigates the effect of over-learning (the circuit adapting to a particular set of test vectors, not the general characteristics of the assessed stream).

Provided the assessed data be random (our null hypothesis), the fitness values from these selected generations should be uniformly distributed on the interval $[0, 1]$. If, however, the evolution was able to produce a circuit successfully distinguishing the pseudo-random cipher output from the reference truly random stream, the fitness value distribution will be biased towards the high end of the interval (lower p-values).

Therefore, at the end of the computation, we perform a Kolmogorov-Smirnov uniformity test [She03] on the vector of fitness values from the selected generations. The run is considered to have found non-randomness in the data (the uniformity hypothesis is rejected) if the p-value resulting from the Kolmogorov-Smirnov test is above the critical value computed for the significance level of $\alpha = 1\%$.

However, due to the randomized nature of generic algorithms, having a single run is insufficient. All EACirc experiments were therefore replicated 1 000 times to eliminate the possible statistical anomalies. Provided the underlying assessed data be random, the uniformly distributed fitness values in selected generations imply the uniformity of the p-values of the Kolmogorov-Smirnov uniformity tests. Thus, to evaluate the set of 1 000 EACirc runs, we inspect the proportion of runs rejecting the null hypothesis (uniformity of the assessed data). If this proportion fluctuates around the set significance level of $\alpha = 1\%$, we cannot reject the hypothesis. If, on the other hand, the proportion wildly deviates from this, we conclude the underlying data was not random with a very high certainty.

To recapitulate the complex interpretation process, see the diagram in figure 4.6.

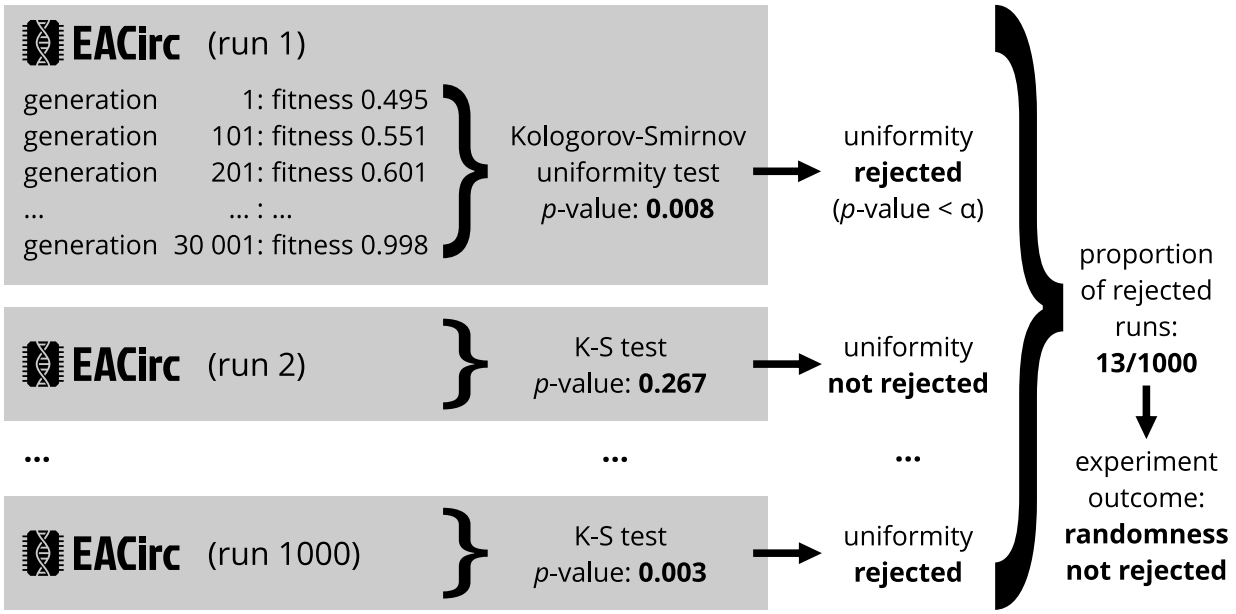


Figure 4.6: The process of evaluating EACirc experiments. For each setting, EACirc run is replicated 1 000 times and the proportion of runs rejecting uniformity is reported. For details on outcome interpretation, see section 5.2.

4.3 Reference experiments

To verify at least a basic sanity of the implementation and proposed experiments, we performed a series of reference tests. These tests use the methodology of real experiments (see section 5.1 for details), but use truly random data instead of the pseudo-random cipher stream.

To verify the outputs of statistical batteries, we generated a stream of random data by EACirc. In order to have the process as similar to the real experiments as possible, a mock-up cipher was created and used in place of the CAESAR candidate. This cipher directly outputs the plaintext as a valid ciphertext, prolonged by a 128-bit tag, sampled from the random generator. Thanks to this, the process of generating the random stream used most of the CAESAR-handling routines.

To test the sanity of EACirc, we run the experiments trying to distinguish tags from this random mock-up cipher from truly random data. In summary, we are trying to distinguish one set of truly random data from another set of truly random data. Obviously, we expected to fail at this. As most of these computations are randomized in nature, the testing was replicated 10 times. The results are summarized in table 4.1.

The presented EACirc results confirm our inability of distinguishing two sets of truly random data from each other – the proportion of runs rejecting the null hypothesis oscillates around the significance level of $\alpha = 1\%$. Nevertheless, it can be seen that the proportion dropped below the value of 0.010 only once in 10 replicated experiments. This may have numerous causes: It may just be a rare case. There may be too little random data for such reference experiments (a single experiment processed $1000 \times 2.24\,\text{MiB}$; we have a total

run (id)	EACirc (proportion of rejected)	NIST STS (x/188)	Dieharder (x/55)	TestU01 (x/159)
1	0.011	187	52	150
2	0.014	187	53	150
3	0.015	188	52	148
4	0.019	187	52	150
5	0.012	188	54	153
6	0.010	188	54	151
7	0.016	185	53	154
8	0.008	187	53	154
9	0.011	188	53	153
10	0.015	188	51	152

Table 4.1: The results of reference experiments running on truly random data. Columns correspond to four different tools used for the analysis. The cells representing results rejecting the null hypothesis using the theoretical thresholds from section 4.1 are coloured in gray. For further discussion of the results, see section 4.3.

of 1.92 GiB of quantum random data). There may be an error in p-value evaluation or CAESAR processing functions. To be conservative in all the following experiments, only proportions higher than 2.5% (based on the numbers in the reference experiments) will be considered as outliers signifying the non-randomness of the assessed data.

The outcomes for NIST STS also confirm the previous findings [Sýs+15] – almost all the tests pass. Therefore, in all subsequent experiments, the expected level of 7 or more failed tests for the conclusion of rejected null hypothesis is used.

The case is different for Dieharder and TestU01. The expected thresholds were 4 and 6 failed tests respectively. For Dieharder, this threshold was crossed in one case. This either is a rare case, or it hints at a small interdependence of the tests. To be on the safe side, we advance the limit for the subsequent experiments to 6 or more failed tests. TestU01 exhibits even more surprising behaviour, breaching the threshold in all but two cases. Taking into account also the workings of the battery (BlockAlphabit running the same set of tests 5 times over), the test independence assumption is rather improbable. Nevertheless, as we need a threshold to be able to evaluate the tests in a comprehensible manner, we choose (somewhat arbitrarily) the limit of at least 18 failed tests (three times the expected number) to indicate found non-randomness.

Although the interpretation of results is not ideal, a much deeper analysis of the used test suites would need to be undertaken to achieve more rigorous bounds. That, however, is not in the scope of this thesis and may be performed in subsequent research.

5 Experiment results

In this section, we describe and evaluate several experiments and try to provide conclusions based on the measured results. In a high-level view, we assess the randomness of authentication tags produced by CAESAR candidate ciphers. In total, we tested 168 different ciphers (53 distinct designs) – for details about submissions not tested, see section 3.2. We differentiate three distinct modes of public message numbers (fixed, counter-based and random). Each case is investigated with four separate tools: a novel problem-solving framework based on genetic programming (EACirc) and three statistical testing batteries (NIST STS, Dieharder and TestU01).

Firstly, in section 5.1, we describe the used CAESAR cipher settings and the method of creating the binary streams for statistical test suites. Secondly, in section 5.2, we summarize the interpretation of all numbers presented in the result tables throughout the chapter. In section 5.3, some conclusions from the measured outcomes regarding the particular CAESAR candidates are drawn. Lastly, in section 5.4, we use the obtained results to reason about the randomness testing tools themselves.

5.1 Experiment settings

The aim of the performed experiments is to assess randomness of authentication tags produced by many authenticated encryption systems. In particular, we inspect tags provided by CAESAR candidates initialized as stated below. An outline of tag generation is also given in figure 5.1.

- **Key**
  The key length is determined by the design or the particular parameter set. The key value was taken randomly but was fixed. For EACirc, the 1 000 independent runs used different keys to allow for variation (otherwise, the same numerical results would be produced).
- **Associated data, secret message number**
  We used two bytes of associated data; the length of the secret message number was determined by the design or the parameter set. Both fields' values were fixed to binary zeros. Note that only three designs used secret message numbers.
- **Plaintext**
  The plaintext used is 16 bytes long, formatted as a single counter starting from zero. We could not use fixed-value plaintext, because, in the case of fixed-value public message numbers, the produced tags would be identical (considering settings of the other arguments). A plaintext of binary zeros would have been possible in the other two modes for public message numbers, but we refrained from doing so to keep the experiments as comparable as possible (with as similar settings as possible).
- **Tag length**
  The length of the produced tag (extra ciphertext bytes when compared to the plaintext length) is determined by the cipher design. However, to normalize input width

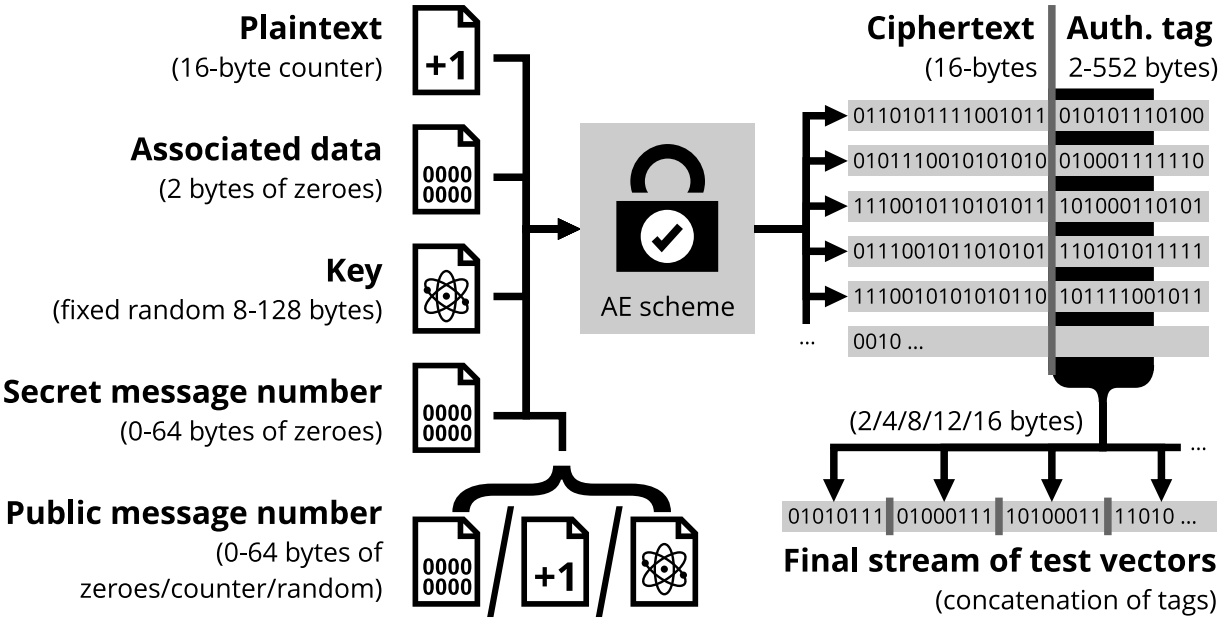


Figure 5.1: The process of creating the tested bitstream – authentication tags produced by the CAESAR candidate are concatenated together. For detailed explanation of the cipher settings, refer to section 5.1.

for the EACirc circuits, we took only the first 128 bits (16 bytes) from the tag. In the case of shorter tags, the test vectors had 96, 64, 32 or 16 bits (the longest applicable). Shorter test vectors mean EACirc inspected proportionally less data for the candidates producing shorter tags. Since these were the tag lengths advised by the submission call, no bits were dropped from the generated tags in most cases.

- **Public message number**
  This was the only parameter explored in different settings. From the nature of the arguments prescribed by the CAESAR API, public message number is probably the argument to be most easily (unintentionally) misused. Security requirements for keys are well known, secret message numbers are usually not used, plaintext and associated data are mostly self-explanatory. Public message numbers are sometimes required to be unique (to have the property of nonces), but sometimes this is not necessary. In a way, we deem testing different modes of public message numbers as examining the robustness of the cipher design.

For testing purposes, we set public message numbers in three distinct ways – each of which was tested separately with all the tools:

1. Fixed to a string of binary zeros for the whole time.
2. Increasing as a counter – each value is unique (but all have a low Hamming weight).
3. Having each value completely random.

EACirc produced the necessary tags on-the-fly. For statistical batteries, a standalone file of 1 GiB was generated using EACirc with identical settings by concatenating the tags. The same file was used for all three suites. To ensure repeatability, the file was generated from

a fixed seed that can be used to re-generate the same stream again, if necessary. Note that the file for statistical batteries was not composed of the bit-to-bit identical tags as those generated by EACirc on-the-fly for its own use. The difference was due to other uses of the randomness generator in the framework during an ordinary run (as opposed to the run dedicated only to stream generation). Furthermore, EACirc requires multiple randomized runs to statistically evaluate the experiment. The most notable difference in the produced tags was the value of the key – fixed to a single value for the file generation (and thus all the statistical tests) but set to other values during the independent 1 000 runs of EACirc.

Using different keys in independent EACirc runs should not be a problem since we aim at assessing the cipher's global behaviour. Although results produced from statistical batteries (with a single key) may reflect the weakness of the particular key, the chance of hitting a weak key is minuscule. As a comparison, DES has 64 keys that should be avoided [Wil04]. Out of the total 2^{56} possibilities, this is a negligible amount.

5.2 Interpretation of results

The goal of this section is to comprehensibly describe the meaning of all the numbers presented in tables 5.1 to 5.8. Rows have all the tested CAESAR candidates, and columns represent the used randomness testing tools grouped into three column-sets according to the used public message number setting. Each candidate also states the length of the test vectors used. The three modes and the reasons for varying test vector lengths are characterized in section 5.1.

For the ease of high-level comprehension, cells rejecting the null hypothesis (claiming the tested data is not random with a chance of error $\alpha = 1\%$) are coloured gray. Note the rejection criterion is different for each tool as recounted below.

The tables list most CAESAR candidates assembled into four sections: the reference *AES/GCM* scheme (table 5.1), 2 schemes withdrawn by the authors (table 5.1), 16 schemes that ended in the first round (tables 5.1 to 5.3) and 27 schemes selected for the second round (tables 5.4 to 5.8). For details on the candidates not tested, refer to section 3.2. Within sections, the submissions are ordered alphabetically to correspond with the CAESAR website. The stated *folder ID* serves as a unique identification of the submission and its parametrization, used as a folder name in the SUPERCOP repository [Vir08], from where the source codes were downloaded.

As for the statistical tools themselves, the presented numbers are not directly comparable – the interpretation is summarized below. Furthermore, let us note that all the tools inspected a different amount of data. For settings, interpretation reasoning and other particulars, see chapter 4.

- **EACirc**
  The displayed number expresses a proportion of runs rejecting the null hypothesis (the uniformity of assessed data) out of 1 000 independent runs. For valid null hypothesis, it should oscillate around 0.010 (1%). We interpret the value as rejecting randomness of the tested data if the proportion is above 0.025.

- **NIST STS**
  A number of passed tests is displayed. If 7 or more tests out of the total 188 failed, we would reject the null hypothesis. In cases denoted by a small star (*) fewer tests (though, always at least 162) were applicable. The rejection threshold should be adjusted in these cases, but the particular value is not stated since almost the entire test suite failed in all such situations.
- **Dieharder**
  Again, we show the number of passed tests. The total is 55 and the threshold for null hypothesis rejection is set to 6 or more failing.
- **TestU01**
  Once more, we present the number of passed tests out of the total 159. The null hypothesis is rejected if at least 18 tests fail.

5.3 Conclusions for CAESAR candidates

Firstly, let's compare the outcomes for the three inspected public message number modes. We expected the random-valued to perform the best, followed by counter-based and then by zero-fixed public message numbers. We reasoned that the more differences there will be among the used values, the „easier" it will be for the cipher to produce a random-looking tag (since it has more entropy to start from). As stated in the submission call, the ciphers were allowed to lose all security in case of reused (public message number, private message number)-pair under the same key. Nevertheless, we expected some (albeit not many) ciphers will be able to retain the apparent randomness of the produced tag – even though it would require an adamant avalanche effect (all arguments are identical apart from a single bit change in plaintext).

From the conducted experiments we see that the primary hypothesis (random values performing better than a counter and much better than zeros) was confirmed. However, none out of the tested candidates passed with the public message numbers fixed to zero. The single bit change in plaintext with all other arguments fixed might not have been enough to cause the avalanche effect needed to produce a tag looking sufficiently random.

Secondly, let's inspect the results for the individual candidates. Tags of just five designs (*AES/GCM*, *Marble*, *AEC-CMCC*, *AES-CPFB*, *Raviyoyla*) were distinguishable from random streams with counter-valued public message numbers. Three of these designs (*Marble*, *AES-CMCC*, *AES-CPFB*) also failed in the random-valued scenario. The evidence is still too weak to deem the designs not secure – it may merely be the case they produce a constant delimiter between the ciphertext and tag, violating the statistical randomness of the created tag. To draw any conclusions, a detailed inspection of the designs (starting with the supporting documentation) would need to be performed. It is, however, worth mentioning that no candidates failing in either counter- or random-valued scenario were selected by the CAESAR committee to the second round of the competition.

There is one more observation to be brought to attention: In two cases (the reference *AES/GCM* and the first-round *AES-CPFB*) the 256-bit version passed while the 128-bit

version was found as non-random. This is highly unexpected and deserves further inspection – it may turn out to be a bug in either the implementation of the candidate submission or in our testing methodology.

5.4 Conclusions for randomness testing tools

Apart from the findings for the CAESAR candidates, the results allow us to gain insights into the capabilities of the used randomness testing tools. Based on the previous works [Ukr13; Sýs+14], we expected the randomness distinguishing abilities of EACirc and NIST STS will be similar while both will be surpassed by Dieharder and TestU01. On the one hand, the observed results showed many deficiencies of EACirc – it performed worse than NIST STS in given tested scenarios. On the other, all three statistical batteries achieved comparable results. However, before any conclusions on the quality of the batteries are drawn, one has to be aware there are many domains in which these tools remain incomparable. They inspect different amounts of data and have different modes of operation (batteries see the stream as a whole, EACirc processes short, distinct test vectors).

There is one case contrary to the general behaviour observed above: *Raviyoyla* with randomly initialized public message numbers for each test vector seems to be successfully rejected from the random stream by EACirc although none of the statistical batteries support such result. It appears very promising but also requires additional inspection and enhanced testing to announce a case of EACirc surpassing all tested statistical batteries.

We can also revisit the set rejection thresholds (although based on the previous research for NIST STS, the set values were adjusted according to the reference experiments in a bit arbitrary way, see section 4.3). The rejection margin for Dieharder (49/55 or less passed tests) was probably too strict. Dieharder's results were just slightly below the threshold in 11 cases in which no other tool hinted at non-randomness in the data. The tests may be more interdependent than was expected.

The case was the other way around for TestU01 – the rejection threshold (141/159 or less passed tests) may have been too benevolent. All seemingly random streams (based on results from the other tools) have above 150 passed tests while all non-random have below 20. In the end, the tests may have been less interdependent than the reference experiments suggested. The only case that would be influenced by the threshold raise is *Raviyoyla* – the only one where EACirc alone rejected the randomness hypothesis. After the adjustment, TestU01 would support the non-randomness claim of EACirc.

To determine the most appropriate rejection levels for the used tools, a wider study similar to the one done by M. Sýs for NIST STS [Sýs+15] would need to be carried out.

Regardless of the exact thresholds, it may seem that Dieharder and TestU01 present more reliable conclusions since proportionally fewer tests passed in non-random cases in these batteries when compared to NIST STS. This is a very delicate matter highly dependent on the process of results interpretation. Therefore, we refrain from drawing such conclusion solely based on the results obtained from experiments performed in this thesis.

Cipher (official name)	**Folder ID** (as used in SUPERCOP [Vir08])	**TV length** (bits)	PMN fixed to zero				PMN counter-based				PMN truly random			
			EACirc (proportion)	**NIST STS** (x/188)	**Dieharder** (x/55)	**TestU01** (x/159)	**EACirc** (proportion)	**NIST STS** (x/188)	**Dieharder** (x/55)	**TestU01** (x/159)	**EACirc** (proportion)	**NIST STS** (x/188)	**Dieharder** (x/55)	**TestU01** (x/159)
AES-GCM	aes128gcmv1	128	1.000	93	3	13	1.000	*14	0	2	0.011	188	51	153
AES-GCM	aes256gcmv1	128	1.000	71	1	13	0.013	188	51	156	0.007	188	54	158
Calico	calicov8	64	0.013	128	3	8	0.009	186	55	156	0.015	188	53	158
Marble	aes128marble4rv1	128	0.016	160	16	6	0.010	168	14	8	0.010	160	16	6
++AE	aeadaes128ocbtaglen128v1	128	0.008	157	16	7	0.012	188	54	154	0.010	188	52	154
++AE	aeadaes128ocbtaglen64v1	64	0.016	144	7	6	0.006	188	52	158	0.008	187	50	157
++AE	aeadaes128ocbtaglen96v1	96	0.011	146	17	5	0.018	185	54	157	0.010	188	53	157
++AE	aeadaes192ocbtaglen128v1	128	0.009	163	15	10	0.011	187	49	157	0.012	187	53	157
++AE	aeadaes192ocbtaglen64v1	64	0.010	130	6	5	0.003	188	54	158	0.013	188	55	154
++AE	aeadaes192ocbtaglen96v1	96	0.012	136	12	6	0.011	188	53	156	0.012	186	52	155
++AE	aeadaes256ocbtaglen128v1	128	0.014	171	17	7	0.014	188	48	158	0.007	188	53	157
++AE	aeadaes256ocbtaglen64v1	64	0.013	132	9	6	0.004	187	54	153	0.005	188	54	156
++AE	aeadaes256ocbtaglen96v1	96	0.010	144	16	9	0.012	188	55	159	0.008	188	54	154
AES-CMCC	cmcc22v1	16	1.000	*0	0	5	1.000	*0	0	5	1.000	*0	0	5
AES-CMCC	cmcc24v1	16	1.000	*0	0	5	1.000	*0	0	5	1.000	*0	0	5
AES-CMCC	cmcc42v1	32	1.000	*0	0	1	1.000	*0	0	11	1.000	*0	0	1
AES-CMCC	cmcc44v1	32	1.000	*0	0	1	1.000	*0	0	11	1.000	*0	0	1
AES-CMCC	cmcc84v1	64	1.000	*0	0	2	1.000	*0	0	4	1.000	*0	0	2
AES-CPFB	aes128cpfbv1	128	1.000	4	0	6	1.000	*0	0	1	1.000	*4	0	8
AES-CPFB	aes256cpfbv1	128	0.009	159	17	7	0.012	188	54	155	0.007	185	53	157
Artemia	artemia128v1	128	0.012	167	11	7	0.015	185	54	157	0.011	187	50	155
Artemia	artemia256v1	128	1.000	*14	0	3	0.013	187	53	154	0.014	186	54	157

Table 5.1: The randomness assessment of the reference AES/GCM, two withdrawn and some first-round CAESAR candidates (part 1/3) in three different public message number modes. For interpretation of displayed numbers and signs, see section 5.2. For drawn conclusions, see section 5.3 and section 5.4.

Cipher (official name)	**Folder ID** (as used in SUPERCOP [Vir08])	**TV length** (bits)	PMN fixed to zero				PMN counter-based				PMN truly random			
			EACirc (proportion)	**NIST STS** (x/188)	**Dieharder** (x/55)	**TestU01** (x/159)	**EACirc** (proportion)	**NIST STS** (x/188)	**Dieharder** (x/55)	**TestU01** (x/159)	**EACirc** (proportion)	**NIST STS** (x/188)	**Dieharder** (x/55)	**TestU01** (x/159)
CBA	cba1	32	0.011	103	3	3	0.010	187	54	155	0.011	188	49	157
CBA	cba2	32	0.008	93	3	3	0.012	187	52	157	0.008	187	52	159
CBA	cba3	64	0.008	124	6	5	0.006	186	54	156	0.006	188	50	157
CBA	cba4	64	0.013	140	7	4	0.009	188	52	158	0.011	188	52	159
CBA	cba5	64	0.013	131	5	6	0.011	186	52	158	0.009	188	54	157
CBA	cba6	96	0.011	137	10	5	0.012	187	54	156	0.009	188	54	159
CBA	cba7	96	0.008	139	13	6	0.010	186	55	157	0.013	188	50	156
CBA	cba8	96	0.009	147	7	7	0.013	188	49	158	0.006	188	52	156
CBA	cba9	64	0.013	131	5	7	0.005	186	51	152	0.008	188	53	157
CBA	cba10	96	0.010	145	11	7	0.013	188	53	155	0.013	187	52	158
Enchilada	enchilada128v1	128	1.000	71	2	15	0.017	187	53	157	0.010	186	52	155
Enchilada	enchilada256v1	128	1.000	77	1	11	0.013	188	54	156	0.016	188	53	155
iFeed[AES]	ifeedaes128n104v1	128	0.017	157	14	11	0.017	188	52	157	0.017	187	55	154
iFeed[AES]	ifeedaes128n96v1	128	0.016	163	10	6	0.011	188	53	153	0.007	187	53	155
SCREAM	iscream12v1	128	0.013	163	19	6	0.008	187	54	157	0.012	188	52	158
SCREAM	iscream12v2	128	0.010	166	14	7	0.010	188	54	157	0.018	188	54	157
SCREAM	iscream14v1	128	0.011	172	13	9	0.008	186	53	153	0.013	186	54	156
SCREAM	iscream14v2	128	0.011	159	13	8	0.013	188	54	154	0.009	188	54	157
KIASU	kiasueq128v1	128	0.017	164	19	6	0.014	188	53	154	0.014	188	55	155
KIASU	kiasuneq128v1	128	0.013	169	18	10	0.006	188	53	154	0.014	188	51	157
LAC	lacv1	64	0.015	139	6	3	0.008	187	55	156	0.013	187	53	153

Table 5.2: The assessment of first-round CAESAR candidates (part 2/3) in three different public message number modes. For interpretation of displayed numbers and signs, see section 5.2. For drawn conclusions, see section 5.3 and section 5.4.

Cipher (official name)	**Folder ID** (as used in SUPERCOP [Vir08])	**TV length** (bits)	PMN fixed to zero				PMN counter-based				PMN truly random			
			EACirc (proportion)	**NIST STS** (x/188)	**Dieharder** (x/55)	**TestU01** (x/159)	**EACirc** (proportion)	**NIST STS** (x/188)	**Dieharder** (x/55)	**TestU01** (x/159)	**EACirc** (proportion)	**NIST STS** (x/188)	**Dieharder** (x/55)	**TestU01** (x/159)
Prøst	proest128apev1	128	0.005	161	22	9	0.015	184	55	156	0.018	185	53	157
Prøst	proest128copav1	128	0.011	160	15	6	0.013	187	50	157	0.010	187	54	155
Prøst	proest128otrv1	128	1.000	*0	0	2	0.008	188	53	152	0.012	186	53	154
Prøst	proest256apev1	128	0.017	159	13	5	0.012	188	53	155	0.009	188	53	158
Prøst	proest256copav1	128	0.012	158	18	7	0.022	188	54	158	0.010	186	54	156
Prøst	proest256otrv1	128	1.000	*0	0	2	0.013	187	54	154	0.016	187	52	156
Raviyoyla	raviyoylav1	128	1.000	22	2	7	1.000	148	28	24	0.295	186	51	144
Sablier	sablierv1	32	1.000	5	1	10	0.000	188	53	158	0.009	187	52	158
Silver	silverv1	128	0.017	160	13	10	0.009	186	53	155	0.009	187	53	158
Wheesht	wheeshtv1mr3fr1t128	128	0.016	166	9	12	0.021	187	53	154	0.020	188	53	157
Wheesht	wheeshtv1mr3fr1t256	128	0.018	159	16	5	0.007	188	54	153	0.011	188	52	156
Wheesht	wheeshtv1mr3fr3t256	128	0.014	166	18	6	0.016	188	54	154	0.009	188	54	157
Wheesht	wheeshtv1mr5fr7t256	128	0.012	172	16	10	0.013	188	55	156	0.013	188	53	154
YAES	yaes128v2	128	0.014	160	15	5	0.011	188	50	153	0.007	188	53	156

Table 5.3: The assessment of first-round CAESAR candidates (part 3/3) in three different public message number modes. For interpretation of displayed numbers and signs, see section 5.2. For drawn conclusions, see section 5.3 and section 5.4.

Cipher (official name)	**Folder ID** (as used in SUPERCOP [Vir08])	**TV length** (bits)	PMN fixed to zero				PMN counter-based				PMN truly random			
			EACirc (proportion)	**NIST STS** (x/188)	**Dieharder** (x/55)	**TestU01** (x/159)	**EACirc** (proportion)	**NIST STS** (x/188)	**Dieharder** (x/55)	**TestU01** (x/159)	**EACirc** (proportion)	**NIST STS** (x/188)	**Dieharder** (x/55)	**TestU01** (x/159)
ACORN	acorn128	128	0.009	159	14	8	0.010	187	51	158	0.012	188	53	158
AEGIS	aegis128	128	0.012	158	13	6	0.015	188	54	157	0.014	187	53	155
AEGIS	aegis128l	128	0.009	160	14	10	0.010	188	54	156	0.012	185	51	158
AEGIS	aegis256	128	0.007	155	16	7	0.015	188	54	158	0.015	187	52	159
AES-COPA	aescopav1	128	0.007	165	23	4	0.013	187	53	153	0.011	187	55	155
AES-JAMBU	aesjambuv1	64	0.013	132	3	10	0.017	187	54	155	0.008	188	54	156
AES-OTR	aes128otrpv1	128	0.014	170	16	8	0.007	188	54	156	0.014	187	55	158
AES-OTR	aes128otrsv1	128	0.011	160	11	7	0.013	188	55	158	0.018	187	52	154
AES-OTR	aes256otrpv1	128	0.013	160	13	6	0.009	187	54	153	0.011	188	53	159
AES-OTR	aes256otrsv1	128	0.013	164	14	9	0.013	188	54	154	0.019	188	55	153
AEZ	aezv1	128	0.014	169	15	9	0.015	187	52	155	0.010	188	52	157
AEZ	aezv3	128	0.016	164	13	6	0.011	188	53	157	0.009	185	50	156
Ascon	ascon128v1	128	0.011	175	15	11	0.014	186	52	155	0.010	188	54	155
Ascon	ascon96v1	96	0.009	150	9	8	0.008	188	53	156	0.012	187	53	153
CLOC	aes128n12clocv1	64	0.009	124	6	10	0.015	187	52	158	0.005	188	52	158
CLOC	aes128n8clocv1	64	0.010	129	4	5	0.011	188	55	158	0.014	188	53	156
CLOC	twine80n6clocv1	32	0.010	87	6	4	0.011	188	54	158	0.010	187	52	159
SILC	aes128n12silcv1	64	0.011	132	10	7	0.012	187	52	153	0.013	187	48	157
SILC	aes128n8silcv1	64	0.007	132	10	7	0.006	188	52	155	0.008	186	52	155
SILC	led80n6silcv1	32	0.004	93	3	7	0.006	188	55	155	0.014	188	51	155
SILC	present80n6silcv1	32	0.010	92	2	4	0.010	187	53	158	0.008	188	54	157
Deoxys	deoxyseq128128v1	128	0.009	168	11	5	0.011	188	54	159	0.017	185	51	158
Deoxys	deoxyseq256128v1	128	0.014	160	17	10	0.014	188	55	158	0.011	187	53	156
Deoxys	deoxysneq128128v1	128	0.016	170	16	9	0.008	185	53	156	0.007	187	55	153
Deoxys	deoxysneq256128v1	128	0.011	162	18	11	0.014	187	52	156	0.018	187	55	158

Table 5.4: The assessment of second-round CAESAR candidates (part 1/5) in three different public message number modes. For interpretation of displayed numbers and signs, see section 5.2. For drawn conclusions, see section 5.3 and section 5.4.

Cipher (official name)	**Folder ID** (as used in SUPERCOP [Vir08])	**TV length** (bits)	PMN fixed to zero				PMN counter-based				PMN truly random			
			EACirc (proportion)	**NIST STS** (x/188)	**Dieharder** (x/55)	**TestU01** (x/159)	**EACirc** (proportion)	**NIST STS** (x/188)	**Dieharder** (x/55)	**TestU01** (x/159)	**EACirc** (proportion)	**NIST STS** (x/188)	**Dieharder** (x/55)	**TestU01** (x/159)
ELmD	elmd1000v1	128	0.012	161	16	9	0.009	187	53	155	0.011	187	55	158
ELmD	elmd1001v1	128	0.009	166	13	8	0.011	188	55	158	0.013	188	49	156
ELmD	elmd101270v1	128	0.009	163	15	8	0.013	188	54	155	0.009	188	51	159
ELmD	elmd101271v1	128	0.013	162	18	7	0.012	188	53	158	0.015	187	53	157
ELmD	elmd500v1	128	0.009	172	15	8	0.011	188	53	156	0.019	187	50	156
ELmD	elmd501v1	128	0.012	166	10	10	0.016	188	54	156	0.012	188	53	158
ELmD	elmd51270v1	128	0.013	165	11	11	0.017	186	50	157	0.006	187	54	158
ELmD	elmd51271v1	128	0.016	163	15	12	0.009	185	53	158	0.015	188	54	155
HS1-SIV	hs1sivhiv1	128	0.016	172	22	6	0.014	187	53	155	0.013	188	55	157
HS1-SIV	hs1sivlov1	64	0.012	131	6	9	0.011	188	54	153	0.009	186	50	156
HS1-SIV	hs1sivv1	128	0.010	165	14	11	0.008	188	54	153	0.017	188	54	158
ICEPOLE	icepole128av1	128	0.012	166	16	7	0.014	188	50	151	0.018	188	54	152
ICEPOLE	icepole128v1	128	1.000	*1	0	5	0.009	186	51	155	0.010	186	53	156
ICEPOLE	icepole256av1	128	0.013	169	17	8	0.012	188	53	158	0.017	188	54	156
Joltik	joltikeq12864v1	64	0.009	142	4	4	0.010	188	52	154	0.009	187	54	154
Joltik	joltikeq6464v1	64	0.010	140	6	6	0.008	187	53	156	0.007	187	53	157
Joltik	joltikeq8048v1	64	0.009	137	5	8	0.008	188	51	152	0.014	188	51	155
Joltik	joltikeq9696v1	64	0.011	119	6	4	0.012	187	52	158	0.004	188	55	156
Joltik	joltikneq12864v1	64	0.017	141	6	7	0.010	187	54	157	0.016	187	54	157
Joltik	joltikneq6464v1	64	0.012	130	9	9	0.011	187	52	157	0.007	187	55	157
Joltik	joltikneq8048v1	64	0.001	134	3	11	0.011	187	48	154	0.011	187	52	154
Joltik	joltikneq9696v1	64	0.004	133	7	6	0.015	188	54	157	0.005	188	51	155

Table 5.5: The assessment of second-round CAESAR candidates (part 2/5) in three different public message number modes. For interpretation of displayed numbers and signs, see section 5.2. For drawn conclusions, see section 5.3 and section 5.4.

Cipher (official name)	**Folder ID** (as used in SUPERCOP [Vir08])	**TV length** (bits)	PMN fixed to zero				PMN counter-based				PMN truly random			
			EACirc (proportion)	**NIST STS** (x/188)	**Dieharder** (x/55)	**TestU01** (x/159)	**EACirc** (proportion)	**NIST STS** (x/188)	**Dieharder** (x/55)	**TestU01** (x/159)	**EACirc** (proportion)	**NIST STS** (x/188)	**Dieharder** (x/55)	**TestU01** (x/159)
Ketje	ketjejrv1	96	0.014	146	8	10	0.012	188	54	155	0.008	187	55	156
Ketje	ketjesrv1	128	0.016	170	18	7	0.020	188	54	156	0.016	187	49	157
Keyak	lakekeyakv1	128	0.018	165	14	6	0.010	187	54	159	0.007	188	54	156
Keyak	oceankeyakv1	128	0.009	160	7	4	0.009	187	54	155	0.013	188	54	156
Keyak	riverkeyakv1	128	0.010	163	9	8	0.023	188	54	151	0.015	188	52	155
Keyak	seakeyakv1	128	0.021	163	18	8	0.011	188	53	157	0.011	188	52	156
Minalpher	minalpherv1	128	0.010	159	20	9	0.008	187	52	158	0.013	188	54	155
MORUS	morus1280128v1	128	0.005	160	9	8	0.017	188	51	153	0.011	188	51	156
MORUS	morus1280256v1	128	0.017	161	8	9	0.009	187	55	154	0.009	188	54	156
MORUS	morus640128v1	128	0.009	165	15	5	0.018	188	54	157	0.014	188	52	156
NORX	norx3241v1	128	0.014	165	14	9	0.008	188	52	159	0.011	186	55	158
NORX	norx3261v1	128	0.013	166	18	6	0.008	188	53	157	0.016	187	50	156
NORX	norx6441v1	128	0.014	156	16	12	0.009	187	51	155	0.018	187	51	154
NORX	norx6444v1	128	0.013	167	16	8	0.013	186	53	156	0.011	188	54	153
NORX	norx6461v1	128	0.016	162	10	7	0.010	187	52	156	0.014	187	54	156
OMD	omdsha256k128n96tau128v1	128	0.012	160	15	5	0.012	187	53	156	0.017	188	55	155
OMD	omdsha256k128n96tau64v1	64	0.013	135	10	6	0.008	185	54	156	0.009	187	53	154
OMD	omdsha256k128n96tau96v1	96	0.010	157	19	9	0.014	188	54	157	0.013	187	53	156
OMD	omdsha256k192n104tau128v1	64	0.010	138	6	6	0.008	187	50	156	0.008	187	51	156
OMD	omdsha256k256n104tau160v1	128	0.014	170	16	9	0.015	187	53	157	0.012	188	53	155
OMD	omdsha256k256n248tau256v1	128	0.010	160	15	8	0.011	186	51	155	0.011	187	53	155
OMD	omdsha512k128n128tau128v1	128	0.011	171	13	7	0.010	188	51	157	0.005	188	52	155
OMD	omdsha512k256n256tau256v1	128	0.017	167	10	6	0.010	188	52	156	0.009	188	52	158
OMD	omdsha512k512n256tau256v1	128	0.017	159	12	7	0.017	187	55	156	0.015	188	50	156

Table 5.6: The assessment of second-round CAESAR candidates (part 3/5) in three different public message number modes. For interpretation of displayed numbers and signs, see section 5.2. For drawn conclusions, see section 5.3 and section 5.4.

Cipher (official name)	Folder ID (as used in SUPERCOP [Vir08])	TV length (bits)	PMN fixed to zero				PMN counter-based				PMN truly random			
			EACirc (proportion)	NIST STS (x/188)	Dieharder (x/55)	TestU01 (x/159)	EACirc (proportion)	NIST STS (x/188)	Dieharder (x/55)	TestU01 (x/159)	EACirc (proportion)	NIST STS (x/188)	Dieharder (x/55)	TestU01 (x/159)
PAEQ	paeq128	128	0.010	164	16	7	0.012	188	52	155	0.015	187	50	157
PAEQ	paeq128t	128	0.017	168	7	8	0.009	188	55	158	0.011	188	50	158
PAEQ	paeq128tnm	128	0.020	158	20	9	0.014	188	54	155	0.008	186	54	158
PAEQ	paeq160	128	0.013	158	11	5	0.013	187	53	155	0.013	187	54	157
PAEQ	paeq64	64	0.016	142	12	9	0.016	188	49	157	0.008	188	52	156
PAEQ	paeq80	64	0.016	130	6	5	0.010	187	52	156	0.017	188	54	152
π-Cipher	pi16cipher096v1	128	1.000	*1	0	3	0.012	187	53	159	0.014	188	52	153
π-Cipher	pi16cipher128v1	128	1.000	*1	0	2	0.015	188	55	157	0.009	188	53	153
π-Cipher	pi32cipher128v1	128	1.000	*0	0	0	0.012	188	52	158	0.008	187	53	155
π-Cipher	pi32cipher256v1	128	1.000	*0	0	2	0.011	188	54	156	0.015	188	53	152
π-Cipher	pi64cipher128v1	128	1.000	*0	0	2	0.011	187	52	156	0.010	186	54	156
π-Cipher	pi64cipher256v1	128	1.000	*0	0	4	0.014	188	48	156	0.008	185	53	154
π-Cipher	pi64cipher256v1oneround	128	1.000	*0	0	8	0.012	187	52	155	0.011	187	53	156
π-Cipher	pi64cipher256v1tworounds	128	1.000	*0	0	2	0.010	187	53	155	0.013	187	53	155
POET	aes128poetv1aes128	128	0.009	169	14	4	0.014	188	52	156	0.015	188	54	154
POET	aes128poetv1aes4	128	0.010	172	11	8	0.013	187	54	157	0.016	188	52	157
PRIMATEs	primatesv1ape120	128	0.013	169	17	11	0.013	187	55	157	0.013	187	51	156
PRIMATEs	primatesv1ape80	128	0.019	159	16	8	0.013	188	52	157	0.013	187	54	156
PRIMATEs	primatesv1gibbon120	96	0.007	154	12	5	0.014	188	55	154	0.015	188	54	157
PRIMATEs	primatesv1gibbon80	64	0.010	128	4	5	0.013	186	52	156	0.006	187	53	156
PRIMATEs	primatesv1hanuman120	96	0.009	130	12	7	0.009	188	53	158	0.016	188	53	156
PRIMATEs	primatesv1hanuman80	64	0.012	148	13	4	0.007	188	53	153	0.011	186	54	157

Table 5.7: The assessment of second-round CAESAR candidates (part 4/5) in three different public message number modes. For interpretation of displayed numbers and signs, see section 5.2. For drawn conclusions, see section 5.3 and section 5.4.

Cipher (official name)	**Folder ID** (as used in SUPERCOP [Vir08])	**TV length** (bits)	PMN fixed to zero				PMN counter-based				PMN truly random			
			EACirc (proportion)	**NIST STS** (x/188)	**Dieharder** (x/55)	**TestU01** (x/159)	**EACirc** (proportion)	**NIST STS** (x/188)	**Dieharder** (x/55)	**TestU01** (x/159)	**EACirc** (proportion)	**NIST STS** (x/188)	**Dieharder** (x/55)	**TestU01** (x/159)
SCREAM	scream10v1	128	0.015	156	18	4	0.014	187	55	155	0.015	188	54	156
SCREAM	scream10v2	128	0.012	163	17	11	0.010	188	52	157	0.013	188	53	154
SCREAM	scream12v1	128	0.018	165	13	6	0.011	187	55	158	0.013	188	53	157
SCREAM	scream12v2	128	0.017	159	16	12	0.010	186	53	154	0.015	188	52	153
SHELL	shellaes128v1d4n64	128	0.009	169	18	4	0.010	187	53	156	0.019	187	53	153
SHELL	shellaes128v1d4n80	128	0.017	169	18	4	0.007	187	53	156	0.015	188	52	153
SHELL	shellaes128v1d5n64	128	0.011	164	22	10	0.011	188	49	157	0.007	188	53	154
SHELL	shellaes128v1d5n80	128	0.009	164	22	10	0.013	188	49	157	0.017	187	55	156
SHELL	shellaes128v1d6n64	128	0.014	160	24	13	0.013	186	54	155	0.013	187	51	159
SHELL	shellaes128v1d6n80	128	0.012	160	24	13	0.013	186	54	155	0.010	188	52	157
SHELL	shellaes128v1d7n64	128	0.019	163	17	9	0.018	186	54	156	0.008	187	53	159
SHELL	shellaes128v1d7n80	128	0.019	163	17	9	0.018	186	54	155	0.014	186	53	155
SHELL	shellaes128v1d8n64	128	0.015	176	15	8	0.010	188	51	157	0.016	187	53	157
SHELL	shellaes128v1d8n80	128	0.013	176	15	8	0.010	188	51	157	0.016	187	53	155
STRIBOB	stribob192r1	128	0.016	158	18	12	0.011	187	54	154	0.014	188	53	156
Tiaoxin	tiaoxinv1	128	0.009	161	24	8	0.012	188	53	158	0.018	188	53	153
TriviA-ck	trivia0v1	128	0.999	140	5	8	0.015	186	52	157	0.005	187	55	154
TriviA-ck	trivia128v1	128	0.993	158	12	8	0.017	188	53	158	0.009	188	54	157

Table 5.8: The assessment of second-round CAESAR candidates (part 5/5) in three different public message number modes. For interpretation of displayed numbers and signs, see section 5.2. For drawn conclusions, see section 5.3 and section 5.4.

6 Summary

The aim of this thesis was to analyze randomness of multiple authenticated encryption systems. In the end, we assessed outputs from 168 distinct schemes (all but six CAESAR submissions) in three different settings (public message number modes) using four different software tools (EACirc, NIST STS, Dieharder and TestU01).

There is a new module for EACirc enabling the randomness assessment of tags produced by authenticated encryption systems. Within this module, there is a codebase of all CAESAR submissions coherently separated as C++ objects compiling in both Windows and Unix environments. The codebase has a comprehensive change tracking system enabling additional detailed inspection of performed changes. There is a set of scripts allowing effortless running of statistical tests.

The conducted tests, taking together thousands of CPU days, were distributed on tens of cores in two facilities. All necessary metadata of all the performed experiments is retained to allow for easy replication if necessary.

6.1 High-level conclusions

The obtained results can be understood in two fundamentally different ways. Looking at the tables row-wise, conclusions can be made for individual CAESAR candidates. Inspecting them column-wise gives us insights into the used randomness testing tools and their relative qualities.

We examined a scenario with random (but fixed) keys, counter-based plaintext and three different settings of public message numbers. As expected, tags produced in configurations with random public message numbers fared better than the ones from counter-based configurations. Both did better than tags from fixed-value public message numbers – no submission had an avalanche effect strong enough to produce random-looking tags in the scenario where all test vectors had the same public message numbers.

Only five CAESAR submissions (*AES/GCM*, *Marble*, *AEC-CMCC*, *AES-CPFB*, *Raviyoyla*) failed to produce seemingly random tags with counter-based public message numbers. For entirely random public message numbers, three candidates failed (*Marble*, *AES-CMCC*, *AES-CPFB*). Importantly, none of these candidates made it to the second round of the competition. Interestingly, in two designs the 256-bit versions significantly outperformed the 128-bit versions.

Regarding the tools used for tag evaluation, EACirc seemed to be the least suitable for the given task, being beaten by all the statistical batteries. The batteries themselves (NIST STS, Dieharder and TestU01) produced comparable results. The only exception is the case of *Raviyoyla*, in which EACirc seems to have outperformed all the other tools. However, when making comparisons, one has to take into account the amount of data inspected by each tool and their different modes of operation.

It turned out that interpreting the results of sets of statistical tests is far from straightforward. The set rejection thresholds influence the conclusions about battery capabilities a lot. To reliably assign such thresholds for Dieharder and TestU01, a thorough inspection of the test interdependence, similar to the one done for NIST STS [Sýs+15], would need to be carried out.

6.2 Proposed future work

The results lead us to several interesting hypotheses requiring further inspection. The candidates exhibiting differences in versions with different parameter sets, as well as those failing in randomness tests, would deserve a deeper manual inspection to prove their potential (in)security.

The used statistical testing suites themselves would be an interesting target for further research. It turned out that interpretation of test suites is quite difficult, and thorough research on test interdependence is necessary. Another prospective direction would be weakening the cipher designs (e.g. by limiting the number of internal rounds) to achieve a fine-grained comparison of the used tools.

A new area of available research concerns the novel EACirc framework. Probably the most beneficial for the cryptographic community would be an analysis of the evolved distinguisher circuits as this could hint at particular cipher weaknesses. Modifications enabling EACirc to process longer inputs or keep custom information from the previously tested vectors might also be helpful. The back-end features of the framework could make advantage of other existing heuristics – we consider superseding the circuits by individuals in the form of simple polynomials in hopes of speeding the evaluation, easing the interpretation and enabling the use of existing analytical tools.

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A Data attachment

The data attachment available in the thesis repository[1] contains source codes and most experimental results organized in the following structure:

- `eacirc`
  Source codes of EACirc (copy of entire project repository with master commit `35c0c0a` from 2016-01-05).
- `eacirc-wiki`
  Project's wiki-based documentation (copy of entire wiki repository with master commit `34cec22` from 2016-01-05).
- `data-eacirc`
  Underlying data for EACirc results presented in chapter 5 further divided into subdirectories according to the public message number mode (`pmn-zero`, `pmn-counter` and `pmn-random`). Only a sample of 10 EACirc runs from 1000 is provided for each case due to size constraints.
- `data-statisitcal-batteries`
  Underlying data for results of statistical batteries presented in chapter 5 further divided into subdirectories according to the public message number mode (`pmn-zero`, `pmn-counter` and `pmn-random`). The tested binary files are omitted due to their size.
- `data-reference`
  Underlying data for reference results presented in section 4.3 for all four statistical testing tools. The tested binary files are omitted due to their size. Only a sample of 10 EACirc runs from 1000 is provided for each case (again, due to size constraints).
- `thesis-src`
  Thesis text source files including bibliography and used images (repository commit `178f932` from 2016-01-09).

1. http://is.muni.cz/th/374297/fi_m/