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**Improvements to the Randomness
Testing Toolkit**

Bachelor's Thesis

TOMÁŠ MAREK

Brno, Fall 2023

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Department of Computer Systems and Communications

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Declaration

Hereby I declare that this paper is my original authorial work, which I have worked out on 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.

Tomáš Marek

Advisor: Ing. Milan Brož, Ph.D.

Acknowledgements

These are the acknowledgements for my thesis, which can span multiple paragraphs.

Abstract

This is the abstract of my thesis, which can span multiple paragraphs.

Keywords

keyword1, keyword2, ...

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Introduction

To be done, now it is only a collection of ideas.

The desired properties of random sequence are *uniformity* (for each bit the probability for both zero and one are exactly $1/2$), *independence* (none of the bits is influenced by any other bit) and *unpredictability* (it is impossible to predict next bit by obtaining any number of previous bits). [1, p. 1-1]

1 Randomness testing

Goal of this chapter is to provide overview of randomness testing process and to explain all used terms. Explanations of both one and two level tests are accompanied by example applications.

1.1 Overview / Introduction

During a randomness test a *random sequence* is tested. In this document, a random sequence is a finite sequence of zero and one bits, which was generated by a tested random number generator. [1, p. 1-1]

Randomness test is a form of *empirical statistical test*, where we test our assumption about the tested data - the *null hypothesis* (H_0). During the randomness test it states that the sequence is *random*. Associated with the null-hypothesis is the *alternative hypothesis* (H_1), which states that the sequence is *non-random*. Goal of the test is to search for evidence against the null-hypothesis. [2, p. 2]

The result of the test is either that we *accept* the null hypothesis (the sequence is considered random), or that we *reject* the null-hypothesis (and accept the alternative hypothesis - the sequence is considered non-random). We reject the null hypothesis when the evidence found against the null-hypothesis is strong enough, otherwise we accept it. Based on the true situation of null hypothesis, four situations depicted in Table 1.1 may occur. [3, p. 417]

Table 1.1: Possible outcomes when assessing the result of statistical test.

TRUE SITUATION	TEST CONCLUSION	
	Accept H_0	Reject H_0
H_0 is True	No error	Type I error
H_0 is False	Type II error	No error

1.2 Single-level testing

A single-level test examines the random sequence directly (compare with 1.3). Before the test user must choose a *significance level*, which determines how strong the found evidence has to be to reject the null-hypothesis. The test yields a *p-value*, which is used to make the accept or reject the null-hypothesis.

The *significance level* (α) is crucial to assessing the test result and must be set before the test. The α is equal to probability of Type I Error. Usual values are $\alpha = 0.05$ or $\alpha = 0.01$ [3, p. 390], for use in testing of cryptographic random number generators lower values may be chosen. [1, p. 1-4] The lower α is set, the stronger the found evidence has to be to reject the null hypothesis.

The randomness test is defined by a *test statistic* Y , which is a function of a finite bit sequence. Distribution of its values under the null hypothesis must be known (or at least approximated). The value of the test statistic (y) is computed for the tested random sequence. Each test statistic searches for presence or absence of some "pattern" in the sequence, which would show the non-randomness of the sequence. There is infinite number of possible test statistics. [4, p. 4]

The *p-value* is the probability of the test statistic Y taking value at least as extreme as the observed y , assuming that the null hypothesis is true. In randomness testing it is equal to the probability that *perfect random number generator* would generate less random sequence. The smaller is the p-value, the stronger is the found evidence against the null-hypothesis. [3, p. 386] The p-value is calculated based on the observed y .

1.2.1 Result interpretation

Decision about the test result is based on the computed *p-value*. If the p-value is lower than the α , we *reject the null hypothesis* (and accept the alternative hypothesis), because strong enough evidence against null hypothesis was found. If the p-value is greater than or equal to the α , we *accept the null hypothesis*, because the evidence against the randomness was too weak. [3, p. 390] It is sometimes recommended to report the *p-value* as well instead of accept/reject only, as it yields more information. [2, p. 90]

The p-values close to α can be considered *suspicious*, because they do not clearly indicate rejection. Further testing of the random number generator on *other* random sequences is then in place to search for further evidence. [4, p. 5] The reason is that *randomness* is a probabilistic property, therefore even the perfect random number generator may generate a nonrandom sequence with low p-value (although it is very unlikely). The further evidence is used to differentiate between the bad generator generating a non-random sequence systematically and the good generator generating non-random sequence 'by chance'. [2, p. 90]

1.2.2 Example

To demonstrate how a single randomness test is made, the Frequency (Monobit) Test from NIST STS battery was chosen. [1, p. 2-2] This test is based on testing the fraction of zeroes and ones within the sequence. For a random sequence with length n the count of ones (and zeroes) is expected to be around $n/2$ (the most probable values are close to $n/2$).

For the Monobit test it is recommended that the tested sequence has at least 100 bits. The test statistic S_{obs} of the Monobit test is defined as

$$S_{obs} = \frac{|\#_1 - \#_0|}{\sqrt{n}}$$

where $\#_1$ is count of ones in the tested sequence (similarly for zeroes) and n is length of the tested sequence. Under the null hypothesis, the reference distribution of S_{obs} is half normal (for large n). The p-value is computed as

$$p = erfc\left(\frac{S_{obs}}{\sqrt{2}}\right)$$

where $erfc$ is the *complementary error function* used to calculate probabilities in normal distribution.

Let

$$\begin{aligned}\epsilon = & 10011001010010000010001001011001101100001101000111 \\ & 10101001010010010011100111001100110010010100111011\end{aligned}$$

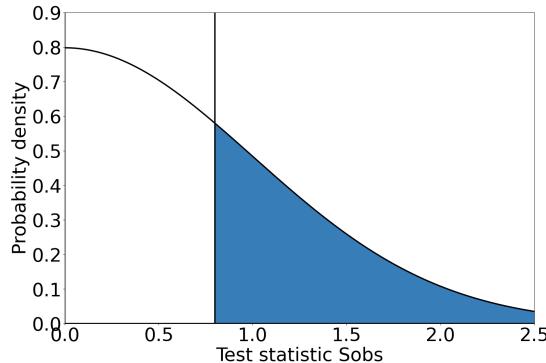


Figure 1.1: Visualization of example p-value for test statistic value $y = 0.8$

be the tested sequence. The test statistic for this sequence is

$$S_{obs} = \frac{|46 - 54|}{\sqrt{100}} = \frac{|-8|}{10} = 0.8$$

and the p-value (visualised at Figure 1.1) is

$$p = erfc\left(\frac{0.8}{\sqrt{2}}\right) \approx 0.423$$

To interpret the test, we compare the computed *p-value* to the chosen α . The $p\text{-value} \approx 0.423$ is greater than both usual $\alpha = 0.05$ and $\alpha = 0.01$, therefore we accept the null hypothesis for both *significance levels* and the sequence ϵ is considered random.

1.3 Two-level testing

The *two-level test* is done by repeating the single-level test n times. The important part is comparing the distribution of produced p-values to the expected distribution. The two-level test allows the random sequence to be examined both locally and globally, while the single-level test examines the sequence only on the global level. This may lead to discovering local patterns, which cancel out on the global level. [4, p. 7]

To apply the two-level test the tested sequence is split into n equal-length disjoint subsequences. The same single-level test is applied to each of the subsequences (as described in Section 1.2) and its *p-values* are collected, resulting in set of n *p-values*¹. The tests are called *first-level tests* and the p-values are called *first-level p-values*. Under the null-hypothesis, the first-level p-values of a given test statistic are uniformly distributed over the interval $(0, 1]$. [5, p. 14]

The crucial part of two-level test is examining the distribution of *observed first-level p-values*. Usually, the *goodness-of-fit* (GOF) tests are applied as the *second-level test*. [4, p. 6] GOF tests are a family of methods used for examining how well a data sample fits given distribution. [6, p. 1] The most used GOF tests in randomness testing are the χ^2 (chi-squared) and Kolmogorov-Smirnov test, another notable tests are the Anderson-Darling and Cramér-von-Mises test. [5, p. 14]

The second-level test is defined by a test statistic Y , which is a function of the first-level p-values. Test statistic value (y) is calculated from the observed *first-level p-values* and then the *second-level p-value* is calculated from y . At last, the second-level p-value is interpreted as in one-level test (as described in Subsection 1.2.1).

Alternatively, a *proportion of subsequences passing the first-level test* is used to examine the fist-level p-values uniformity. Under the null-hypothesis, it is expected for $n \cdot \alpha$ subsequences to be rejected (i.e. to have p-value $< \alpha$) by the first-level test (be a subject to Type I Error). The ratio of sequences passing the first-level test is expected to be around $1 - \alpha$, different ratio indicates non-uniformity of observed first-level p-values. [1, p. 4-2] No p-value is reported in this case, only the ratio.

1.3.1 Kolmogorov-Smirnov test

The one-sample Kolmogorov-Smirnov (KS) test is used in randomness testing to compare the observed first-level p-values to the uniform distribution. The Kolmogorov-Smirnov test is built on comparing the cumulative distribution function (CDF)² of the expected distribution

1. Note that the p-values are not subject to accept/reject decision.
2. For a given distribution and value x , the CDF returns the probability of drawing a value less than or equal to x .

and the empirical cumulative distribution function (eCDF)³ of the observed samples.

In first variant, two test statistics are calculated. The test statistic D^+ (D^-) is the maximal vertical distance between CDF and eCDF above (under) the CDF. In second variant, only the test statistic D (maximal vertical distance between CDF and eCDF) is measured. Formally, the test statistics are defined as

$$\begin{aligned} D^+ &= \sup_x \{F_n(x) - F(x)\} \\ D^- &= \sup_x \{F(x) - F_n(x)\} \\ D &= \sup_x \{|F_n(x) - F(x)|\} = \max(D^+, D^-) \end{aligned}$$

where $F(x)$ is the CDF and $F_n(x)$ is the eCDF [6, p. 100].

1.3.2 Chi-squared test

The Pearson's χ^2 test is used to find statistically significant difference between frequencies of categories in two sets of categorical data. The first-level p-values are split into k equal-width bins (categories) and their respective frequencies are counted. The counted frequencies are compared to the expected frequencies.

For data with k categories the test statistic χ^2 is defined as

$$\chi^2 = \sum_{i=1}^k \frac{(x_i - m_i)^2}{m_i}$$

where x_i is the observed frequency in i -th category and m_i is the expected frequency in i -th category. For first-level p-values, the expected frequency is equal in each interval. For a correct test the expected frequency in each category must be at least five. [7, p. 171]

1.3.3 Example

In the two-level test example, I will test one sequence using both one and two-level tests to demonstrate the difference between them. First, the sequence is tested using the one-level Frequency (Monobit) test

3. For a set of observed data and value x , the eCDF returns the probability of drawing a value less than or equal to x .

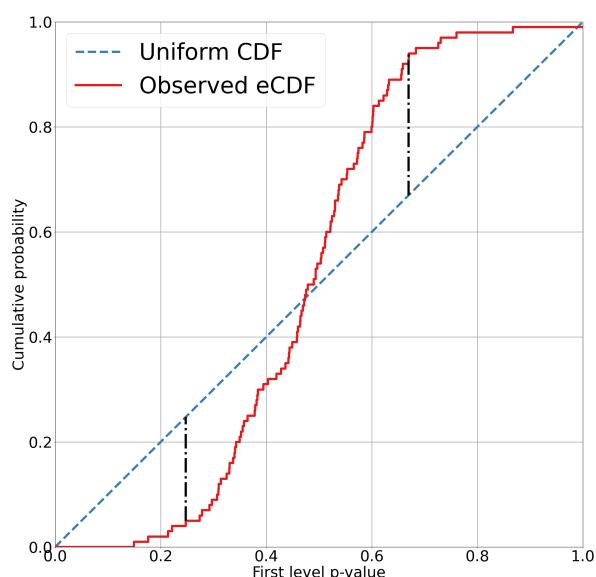


Figure 1.2: Visualization of Kolmogorov-Smirnov test statistics for expected uniform distribution and observed data sample.

Table 1.2: First-level p-values produced by Monobit test

p-value	occurrences
$1.52 \cdot 10^{-23}$	30
0.31	5
1.0	15

from NIST STS battery.[1, p. 2-2] Then the same sequence is assessed by the two-level test using the Frequency test as the first-level test and KS and χ^2 tests as second-level test. Let

$$\begin{aligned}\epsilon = & 15 * (100 \text{ consecutive zeroes}) + \\ & 15 * (100 \text{ alternating ones and zeroes}) + \\ & 5 * (55 \text{ zeroes and } 45 \text{ ones}) + \\ & 15 * (100 \text{ consecutive ones})\end{aligned}$$

be the tested sequence.

Result of the one-level Frequency test for the sequence ϵ is p-value ≈ 0.479 . The null hypothesis is accepted for both $\alpha = 0.01$ and $\alpha = 0.05$ and the sequence ϵ is considered random. This sequence however clearly contains a pattern, therefore the probability of it being generated by a perfect random number generator is very low.

For the two-level test, the sequence ϵ is split into $n = 50$ disjoint 100 bit long subsequences. The Monobit test is applied on each subsequence resulting in set of first-level p-values shown in Table 1.2.

Last step is to apply the goodness-of-fit tests. The first applied test is the Pearson's χ^2 test with $k = 10$ (number of categories), the expected frequency of p-values in each category is five. The statistic of the test is

$$\chi^2 = \sum_{i=1}^{10} \frac{(x_i - 5)^2}{5} = 180$$

and the p-value of this test is $p \approx 5.06 \cdot 10^{-34}$. The null hypothesis is rejected for both $\alpha = 0.01$ and $\alpha = 0.05$.

Next, the Kolmogorov-Smirnov test is applied. The eCDF is calculated and then the D statistic is computed. The statistic is $D = 0.6$ and results in p-value $\approx 9.63 \cdot 10^{-18}$. Again, the null-hypothesis is re-

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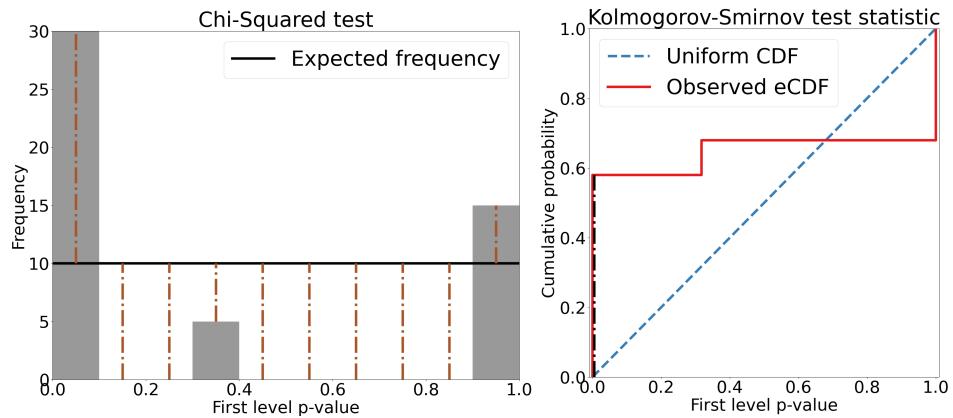


Figure 1.3: Visualisations for χ^2 and KS tests for two-level test example.

jected for both $\alpha = 0.01$ and $\alpha = 0.05$ and the sequence is considered non-random.

2 Programms for randomness tesing

In this chapter, available programms for randomness testing are presented. First section describes *statistical testing batteries* (later often referred to as batteries). The second section shows *randomness testing toolkits*, which encompass several batteries together. Overview of setup and output is given in both sections.

2.1 Statistical testing batteries

Statistical testing battery (suite) is a set of randomness tests with pre-defined parameters that allows the user to conveniently apply randomness tests. [2, p. 5] Because all of the batteries share significant similarities, an *abstract battery* is presented to demonstrate the principles. Then, each battery is presented in more detail, mapping its features to the *abstract battery*. The described batteries are Dieharder, NISTS STS, several batteries from TestU01, FIPS ans BSI.

An *abstract battery* consist of n individual tests, which are distinguished by *test IDs*. Usually, one individual test maps to one two-level test. Some individual tests consist of more *subtests*, which are all executed at once when the individual test is executed.

Each *subtest* maps to one *two-level test*. The first-level test statistics of subtests are usually related to each other by using the same operation on the tested sequence. For example, the Diehard Craps Test plays 200 000 games of craps. The two calculated first-level test statistics are based on number of wins and GOF test of distribution of throws needed to end the game. [8]

Variant of the test is an individual test that is parametrized to search for modified pattern in the data. Only some individual tests allow such parametrization. Usually, all possible *variants* of given individual test are executed. [9, p. 2]

The following settings are available in *abstract battery*. They can be set either *globally* with same values for all *individual tests*, or *individually*:

- *number of first-level tests* - Sets how many times the first-level test is repeated (i.e. how many first-level p-values will be produced).
- *size of first-level subsequence* - Sets how long are the subsequences used for first-level test.

- choose variant (if applicable for given test).

Originally, the testing batteries were designed to test the random number generators by taking data directly from them as needed. However, common way to test RNG is to take a sample of output, store it into a file and then test contents of the file. The tested file is rewound to the beginning before each individual test (all tests are executed over the same sequence). When the generator is tested directly, every test is executed on 'fresh' sequence.

Testing files leads to need of *file rewind* detection, which is important part of each battery. File rewinds occurs when the tested file is not large enough for given test configuration. In this case, some parts of the file are tested twice during one test and the results may be biased. The required data size is calculated as *number of first-level tests* · *size of first-level sequence* and it is up to the user to prevent *file rewinds* by configuring the batteries.

2.1.1 Dieharder

The *Dieharder* battery was developed by Robert G. Brown at Duke University[8] as an extension to an older *Diehard* battery (created by George Marsaglia). The *Dieharder* is available from [10] maintained by Dirk Eddelbuettel or as package in some Unix distributions.

The *Dieharder* contains 31 individual tests. However, four of them are marked as 'Suspect' or 'Do Not Use' and should not be used. Test variants are possible in four tests.

The *Dieharder* allows all settings as described in the *abstract battery*. They are:

- *psamples* argument sets the number of first-level tests. Default value is 100.
- *tsamples* arguments sets the length of first-level subsequences. Units are *random entities*, which are different size for each test. The tests have various default values, some tests ignore this argument.
- *ntup* argument chooses *test variant* for relevant individual tests.

Results of the *Dieharder* are printed to standard output in a table of results. Each row of the table contains results of one individual test or subtest. Columns contain *test name*, value of *ntup* argument (if applicable, usually 0 otherwise), *tsample* and *psamples* values. Last two

columns are the *second-level p-value* and *assessment*. Dieharder output can be modified using *output flags*, including the possibility to print all first-level p-values. Example of Dieharder output can be found in Appendix A.

The *file rewinds* are detected by Dieharder automatically. In such case message '# The file file_input_raw was rewound <n> times' is printed to error output. Alternatively, by using dedicated output flag, the amount of data used and this message are printed to standard output after each individual test.

2.1.2 NIST STS

The NIST¹ STS² was implemented by NIST [1] and is available from [11]. Due to the original implementation being slow, optimized version was developed by CRoCS³ FI MU [12] available from [13]. *NIST STS* contains 15 individual tests with no variants. Allowed settings are:

- *Stream count* argument denotes the number of first-level tests and must be set by the user. For a statistically meaningful result of second-level test should be at least 55.
- *Stream size* argument sets the length of first-level subsequences in *bits* and must be set by the user. The tests have various recommendations for minimal size.

The second-level p-value is computed using the χ^2 test after dividing the first-level p-values into $k = 10$ categories. The NIST STS also calculates the proportion of subsequences passing the first-level test. [1, p. 4-1].

Tests results are stored in files inside *experiments/AlgorithmTesting* folder. Table with overview of results is in file *finalAnalysisReport.txt*. Each row contains one individual test or subtest. First 10 columns are observed frequencies of first-level p-values in given category. The *second-level p-value*, *proportion of subsequences passing the first-level test* and test name follow.

More result information for each test is stored in corresponding folders. In file *stats.txt* the first-level p-values, test statistics and other computational information are stored. In file *results.txt*, only the first

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 2. Statistical Test Suite
 3. Center for Research on Cryptography and Security

level p-values are stored. Example of output is available in Appendix A.2.

The file rewinds are detected automatically by the battery. In such case, message 'READ ERROR: Insufficient data in file.' is printed to standard output.

2.1.3 Test U01

TestU01 was developed by Pierre L'Ecuyer and his team at Université de Montréal to be a state-of-the-art software library oriented on testing of random number generators [4] and is available from [14]. It contains several batteries, most important are the *SmallCrush*, *Crush*, *BigCrush*, *Rabbit*, *Alphabit* and *BlockAlphabit*. Because TestU01 is a software library only, custom command-line interface was created by Lubomír Obrátil available from [15], which is described in this subsection.

The TestU01 does not apply a two-level test, but only allows to repeat the single-level test. In TestU01, the *individual test* maps to the repeated *single-level test*. One run of the signle-level test is called *repetition*. If the user wishes to apply the second-level test, they have to examine the distribution of p-values on their own.

Each battery in TestU01 allows for a different set of user settings. All possible arguments in TestU01 are:

- *repetitions* argument sets how many times the single-level test is executed. This argument is used in all batteries.
- *bit_nb* argument sets the length of first-level subsequences in *bits*. Applicable (and mandatory) only for Rabbit, Alphabit and BlockAlphabit.
- *bit_w* argument is used to choose test variant in *BlockAlphabit* battery.

The output format is same of for all of TestU01 batteries and is printed to standard output. Only one individual test is executed during one battery run, for which the following is printed. For each repetition of single-level test the test name and all test parameters are printed. Then the test static value and its corresponding p-value are printed (or more values and p-values, if the individual test consists of more subtests). After each repetition, a *generator state* is printed, containing information about how many data were used in all single-level tests

so far. And the end of the individual test report, list of all p-values is printed. Example output is in Appendix A.3.

File rewind detection is done partially by the batteries using the *generator state* information, however it is up to the user to interpret it. The *generator state* contains three fields - *bytes need for testing* (number of bytes that were indeed used for testing), *bytes read from file* (number of bytes that were read from tested file) and *total number of file rewinds*.

Because the data are read from file in 10MB long blocks, the number of file rewinds may be positive, but the number of *bytes needed for testing* will be lower than the actual file size, causing a false alarm. It is up to the user to manually check this situation.

SmallCrush, Crush, BigCrush

Batteries from the *Crush* family were created to test general use random number generators. The batteries contain 10, 96 and 106 tests with increasing demand for data size and runtime. The intended use is to apply SmallCrush for a quick assessment. If the sequence is accepted, more stringent Crush and BigCrush batteries are applied. The size of first-level sequence cannot be changed. [2, p. 242]

Rabbit

The Rabbit battery contains 26 individual tests. The *bit_nb* argument must be set by the user to a value of at least 500. At most *bit_nb* will be used for first-level subsequence size. [2, p. 152] However, several tests require significantly longer subsequence than 500 bits. Some tests use significantly shorter subsequence than specified by *bit_nb*. Problems with the *bit_nb* argument are deeper described in Subsection 3.1.4.

Alphabit and BlockAlphabit

Both Alphabit and BlockAlphabit batteries contain the same nine individual test. In the BlockAlphabit battery, the tested data are transformed to deploy *test variants*. The test variant is chosen by the *bit_w* argument parametrizing the transformation, which takes values from set {1, 2, 4, 8, 16, 32}. [2, p. 155] Size of the first-level sequences will be *at most* the size set by *bit_nb* argument.

2.1.4 FIPS Battery

The FIPS⁴ battery contains five tests and is based on FIPS 140-2 standard. [16] Custom command-line interface of the battery was created by Patrik Vaverčák available from [17]. The interface is based on implementation taken from [18]. No test variants are available and the length of first-level sequence is set to 2500 bytes and cannot be changed [9, p. 20]. Only one arguments is available:

- *bytes count* argument sets how many bytes will be used for testing *in total*, determining the *number of first-level tests*

Output of FIPS battery is printed to standard output and in user-specified file in JSON⁵ format. First, information about accepting or rejecting the null-hypothesis is printed. Then a list of individual tests results is printed. For each individual test, the test name, number of failures and number of runs is printed. Example output is in Appendix A.4

File rewinds are detected automatically by the battery. In such case, the battery will not run and will print message 'Error (<filename>) ! File is not big enough' to error output.

2.1.5 BSI battery

The BSI⁶ battery contains nine test and is based on series of standards released by BSI. [19] Custom command-line interface was created by Patrik Vaverčák, available from [17]. The tests implementations were extracted from the ParanoYa application. [9, p. 16]

No test variants are available in the BSI battery. Each test has its own preset *first-level subsequence size*, which cannot be changed. One argument is available for the battery:

- *bytes count* argument sets how many bytes will be read from the tested file. The number of *first-level tests* is calculated based on this value.

Output of BSI battery is printed to standard output and in user-specified file in JSON format. It contains list of individual tests results. For each individual test, a name and information whether *total error*

4. Federal Information Processing Standards

5. JavaScript Object Notation

6. Bundesamt für Sicherheit in der Informationstechnik

occurred is printed. If no *total error* occurred, number of failures and number of runs is printed as well. Example output is available in Appendix A.5.

File rewinds are detected automatically by the battery. In such case, the battery will not run and will print message 'File is not big enough' to error output.

2.2 Testing toolkits

In the previous section different randomness testing batteries were described. The typical user, however, uses more than one battery, which means installing and running each testing battery individually. Also it is strongly recommended (sometimes even needed) to set up parameters for each test from the battery individually based on size of the tested file and to run this test manually.

Since this approach is not convenient, CRoCS FI MU created the Randomness Testing Toolkit (*RTT*).[20] This toolkit allows users to run and configure eight test batteries using the same command.

This work was followed by Patrik Vaverčák from Faculty of Electrical Engineering and Information Technology at Slovak University of Technology. He created newer variant of *RTT* called Randomness Testing Toolkit in Python (*rtt-py*). [9]

2.2.1 Randomness Testing Toolkit

RTT was created in 2017 and its main idea was to combine *Dieharder*, *NIST STS* and all batteries from *TestU01* mentioned in Subection 2.1.3 into one program. It was written in C++ and the concept is that *RTT* acts only as a unified interface of the batteries. Each test battery is executed by *RTT* as a separate program. The *RTT* then collects the output and processes it into a unified format. [20, p. 8]

RTT is available from CRoCS GitHub repository [21]. All of the batteries used in *RTT* are available from a single GitHub repository [15]. Before running, user has to install both the *RTT* and used batteries as described GitHub project wiki. If the user intends to run NIST STS, the *experiments* folder has to be moved (or linked) to *working directory* of *RTT*. This is not noted anywhere.

RTT settings

The *RTT* needs to be set up by the user before running. The first part of user settings contains *general settings* of the *RTT*, the second part contains individual *batteries configurations*. Each of these parts is stored in its own JSON file.

The *general settings* are stored in *rtt-settings.json* file, which has to be located in the working directory of the *RTT* [20, p. 10]. These settings are not expected to change. The most important setting from the general part are paths to the executable binaries of individual statistical test batteries. This is the only setting that has to be manually filled in by the user.

The storage database can also be filled in by the user, but this functionality is optional. The following general settings have implicit values and do no need to be changed unless the user wishes to. They are paths to storage directories for results and logs of individual runs and execution options (test timeout and maximal number of parallel executions of tests). Example of *rtt-settings.json* file is in Appendix B.1.

The battery configurations are dependant on the size of the tested file, therefore the file with the battery configuration is specified for each run of the *RTT* as one of its arguments. These configurations are different for each battery (see Section 2.1), but they all follow the same format and are stored together in a single file. [20, p. 11] The *RTT* contains several prepared battery configurations for various sizes of tested file. Example of battery configuration file is in Appendix B.2.

For each battery, the settings are split into two parts - *defaults* and *test-specific-settings*. The *defaults* section contains IDs of individual tests to be run and default values of all battery arguments. The *test-specific-settings* is a list of all tests whose settings are different than those in *defaults* (along with new settings) or tests which employ test variants. In the second case, all variants to run are listed in entry for the given individual test.

RTT output

The output of *RTT* is in a plain text format. The most important part of the output is the direct report, which is saved in the *results* directory. At the beginning of the report are general information – the name of

2. PROGRAMMS FOR RANDOMNESS TESING

```
-----  
Diehard Birthdays Test test results:  
  Result: Passed  
  Test partial alpha: 0.01  
  
User settings:  
  P-sample count: 65  
*****  
  
Kolmogorov-Smirnov statistic p-value: 0.46269520      Passed  
p-values:  
  0.01554128 0.01704044 0.07338199 0.08890865 0.13047059  
  0.14641850 0.14648858 0.14985241 0.15741014 0.17234854  
  0.17570707 0.18313806 0.19708195 0.21929163 0.23582928  
  0.23875056 0.24659048 0.24810255 0.26921690 0.29350665  
  0.29444024 0.29618689 0.30017915 0.30767530 0.32816499  
  0.33671597 0.33723518 0.33723518 0.35046577 0.36986762  
  0.38616538 0.40739822 0.42316216 0.42606175 0.42712489  
  0.46376818 0.47710967 0.51301110 0.55638736 0.58615965  
  0.58816320 0.62212002 0.63106447 0.65794861 0.66078115  
  0.66209483 0.67060673 0.69336319 0.70343506 0.72259414  
  0.74451995 0.79749441 0.81986290 0.85442793 0.88851953  
  0.88897431 0.89604503 0.92240447 0.93852901 0.93852901  
  0.95468456 0.96540827 0.96785289 0.96922576 0.99790555  
=====
```

Figure 2.1: The example of individual test report from the RTT

the tested file, the name of the used battery, ratio of passed and failed individual tests and battery errors and warnings in case there were any.

After the general information is a list of results of individual tests in a unified format. The fist part of the individual test report contains the name of the test and user settings. The second part of the individual test report is the second-level p-value alongside the name of statistic used (or more, in case the individual test consists of more subtests). At the end of the individual test report is a list of first-level p-values produced by the test. Example of the output can be seen in Figure 2.1.

2.2.2 Randomness Testing Toolking in Python

The Randomness Testing Toolkit in Python (*rtt-py*) was created by Patrik Vaverčák. It is supposed to be an improved version of RTT sharing the same concept [9, p. 24] and it was written in Python.

The included batteries are Dieharder, NIST STS, FIPS battery and BSI battery. *Rtt-py* also includes Rabbit, Alphabit and BlockAlphabit batteries from TestU01. The Crush family batteries are not run, even though arguments of *rtt-py* suggest that they are included. The *rtt-py* allows for multiple files to be tested at once.

The *rtt-py* is available from [22] and implementations of all used batteries are available from [17]. Before running, both the *rtt-py* and the batteries have to be installed as described in the project's README.

Rtt-py settings

The settings of *rtt-py* use same format as the original *RTT* (as described in Subsection 2.2.1). The *general settings* from the *RTT* should be one-way compatible with *rtt-py* [9, p. 25]. In reality there is a problem with settings for the NIST STS's experiments directory. Also, no database connection is implemented in *rtt-py*, therefore the *mysql-db* attribute is ignored. [22]

The second part of user settings are the battery configurations. They use the same format as in *RTT* (as mentioned in 2.2.1) and are interchangeable. [9, p. 25] The user has to keep in mind that the *rtt-py* uses FIPS and BSI batteries, which are not used in *RTT*.

Rtt-py output

The *rtt-py* creates output in two formats – *CSV*⁷ and *HTML*⁸. [9, p. 36] Both of these report formats contain overview table. Each row from the table represents results of one individual test or subtest. The first column contains the name of the test and the name of the battery it belongs to. The second column contains *failure rate* - ratio of sequences not passing the first-level test.

Each of the following columns is named after one tested file. The record contains either second-level p-value reported by the test, or number of failed runs – this depends on the battery. Example of this table can be seen at figure 2.2.

7. Comma-separated values
8. Hypertext Markup Language

	Failure rate	./input2/1000MB.dat	./input2/1000MB_2.dat
rgb_minimum_distance_0 (DIEHARDER)	0.0	0.754103	0.407390
rgb_permutations_0 (DIEHARDER)	0.0	0.931074	0.184047
diehard_operm5_0 (DIEHARDER)	0.0	0.228052	0.680182
sts_monobit_0 (DIEHARDER)	0.0	0.279259	0.096535
sts_serial_0 (DIEHARDER)	0.0	0.279259	0.096535
sts_serial_1 (DIEHARDER)	0.0	0.972893	0.052121
sts_serial_2 (DIEHARDER)	0.0	0.621721	0.618407

Figure 2.2: The example of the overview table from the *rtt-py*

The output in the HTML format contains than the output in the CSV format. For each battery and for each tested file an HTML file with reports is generated.

In each report file there is a list of reports for each individual test or subtest from the given battery containing the result (either reported p-value, or number of failed runs). It may contain additional information such as settings of the test or other information connected to the result, depending on the battery and on the executed test. Example of the report can be seen in figure 2.3

Input file:/input2/1000MB.dat

Test 0: diehard_birthdays	
ntuples	0
tsamples	100
psamples	65
p-value	0.42485416

Test 1: diehard_operm5	
ntuples	0
tsamples	1000000
psamples	1
p-value	0.22805181

Figure 2.3: The example of HTML Dieharder report from the *rtt-py*

3 Tests Analysis

This chapter aims to provide more information about the tests from the practical point of view. First, I analysed how much data the tests use to help with configurations of the batteries. As next, I measured how much time each test from the batteries takes to run. Data from both parts were used to create a program for automatic creation of test configurations for *RTT* and *rtt-py* - the *Configuration Calculator*. Last section will done?

3.1 Data Consumption

As mentioned in Subsection 2.1, import part of preventing *file rewinds* is correct configuration of the tests. This is a complicated task, because the user has to know size of test first-level subsequences. To help with this task, I performed analysis of sizes of first-level subsequences for Dieharder, SmallCrush, Crush and Rabbit batteries.

The NIST STS, Alphabit and BlockAlphabit batteries are not shown because the size of first-level subsequence is set by the user. Unlike in Rabbit battery, the tests from mentioned batteries were observed to use the amount of data specified by their arguments. The BigCrush battery was skipped because its first-level subsequence are larger than the currently intended use of RTT.

3.1.1 Introduction

The idea was to run all tests from the batteries and calculate how many bytes were used for each individual test or test variant based on data provided by the batteries. Based on this information, a table for each battery containing this information was created.

The tests are divided into categories based on two properties. The first property is user's influence on the first-level subsequence size. Second property is if *all* runs of the *same* first-level tests use *equal* size of first-level subsequence, or if the first-level subsequence size fluctuates between runs.

In the subsequent text, I use the following terminology. Based on the first property, the tests are called as:

- *Tests with configurable size* are the tests where the size of first-level subsequence can be set by the user.
- *Tests with fixed size* have predefined and unchangable first-level subsequence size.

Based on the second property, the categories are called:

- *Tests with constant size* are the tests where the first-level subsequence is equal for all runs.
- *Tests with variable size* are the tests where the first-level subsequence size fluctuates.

The size of the first-level subsequence in the tests with variable size is determined by *content* of the sequence. TODO: EXAMPLE FROM DIEHARDER. For an *individual* test from this category and for random content of the sequence, the *real* size of the first-level sequence fluctuates around *some* value.

To examine how long are the first-level sequences of tests with variable size, I run each test from this category at least 100 times on different *random* data (taken from /dev/random). Tests from this category are presented in their own tables containing mean length of the subsequence and differences between mean and lowest and highest observed length.

To verify that tests with constant size are indeed constant, I run them several times with different number of first-level sequences. The table for them contains only length of the subsequence.

3.1.2 Dieharder

In Dieharder both tests with configurable and fixed size are present. All tests with configurable size have a default setting for first-level sequence size, which is usually used. Therefore all tests from this battery are in the analysis viewed as tests with fixed size. The subsequence sizes are presented in three tables.

Table 3.1 contains tests with *variable sizes*. The tests with *constant sizes* are split in two tables. In Table 3.3, the tests with *no variants* are shown, the tests with *varints* are shown in Table 3.2.

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Table 3.1: First-level subsequence sizes for Dieharder tests with *variable* sizes.

Test ID	average	Δ min	Δ max
13	9,225,521	0.039%	0.038%
16	5,402,335	0.126%	0.077%
207	452,016,414	0.019%	0.015%
208	116,881,517	0.047%	0.014%

3. TESTS ANALYSIS

Table 3.2: First-level subsequence sizes for Dieharder tests with *constant* sizes and test variants.

ID	ntup	bytes	ID	n	bytes
200	1	800,004	203	7	32,000,000
200	2	1,600,004	203	8	36,000,000
200	3	2,400,004	203	9	40,000,000
200	4	3,200,004	203	10	44,000,000
200	5	4,000,004	203	11	48,000,000
200	6	4,800,004	203	12	52,000,000
200	7	5,600,004	203	13	56,000,000
200	8	6,400,004	203	14	60,000,000
200	9	7,200,004	203	15	64,000,000
200	10	8,000,004	203	16	68,000,000
200	11	8,800,004	203	17	72,000,000
200	12	9,600,004	203	18	76,000,000
201	2	80,000	203	19	80,000,000
201	3	120,000	203	20	84,000,000
201	4	160,000	203	21	88,000,000
201	5	200,000	203	22	92,000,000
202	2	800,000	203	23	96,000,000
202	3	1,200,000	203	24	100,000,000
202	4	1,600,000	203	25	104,000,000
202	5	2,000,000	203	26	108,000,000
203	0	4,000,000	203	27	112,000,000
203	1	8,000,000	203	28	116,000,000
203	2	12,000,000	203	29	120,000,000
203	3	16,000,000	203	30	124,000,000
203	4	20,000,000	203	31	128,000,000
203	5	24,000,000	203	32	132,000,000
203	6	28,000,000			

Table 3.3: First-level subsequences sizes for Dieharder tests with *constant* sizes and no variants.

ID	bytes	ID	bytes
0	153,600	12	48,000
1	4,000,020	14	796
2	5,120,000	15	400,000
3	2,400,000	17	80,000,000
4	1,048,584	100	400,000
5	8,388,608	101	400,000
6	5,592,416	102	400,000
7	2,621,484	204	40,000
8	256,004	205	614,400,000
9	5,120,000	206	51,200,000
10	96,000	209	260,000,000
11	64,000		

3.1.3 TestU01 SmallCrush and Crush

In the SmallCrush and Crush batteries, only tests with *fixed* size are present. Both batteries contain tests with *variable* size, which are shown in Table 3.4 for SmallCrush and in Table 3.6 for Crush. The tests with *constant* sizes from SmallCrush are in Table 3.5, from Crush in Table 3.7.

Table 3.4: First-level subsequence sizes for *SmallCrush* tests with *variable* sizes.

Test ID	average	Δ min	Δ max
3	204,733,510	0.563%	0.725%
5	98,731,035	0.095%	0.087%

3. TESTS ANALYSIS

Table 3.5: First-level subsequence sizes for *SmallCrush* tests with *constant* sizes.

Test ID	bytes
1	40,000,000
2	40,000,000
4	102,400,000
6	48,000,000
7	204,800,000
8	28,800,000
9	120,000,000
10	20,000,000

Table 3.6: First-level subsequence sizes for *Crush* tests with *variable* sizes.

Test ID	average	Δ min	Δ max
27	1,333,326,306	0.0163%	0.0166%
28	1,333,331,101	0.0188%	0.0170%
29	1,974,653,548	0.0189%	0.0196%
30	1,974,640,110	0.0164%	0.0146%
31	3,200,051,704	0.0204%	0.0306%
32	3,199,995,653	0.0380%	0.0244%
33	5,120,635,483	0.1408%	0.1618%
34	5,119,635,549	0.1399%	0.2516%
55	1,653,334,290	0.0065%	0.0060%
64	320,000,610	$5.31 \cdot 10^{-5}\%$	$4.43 \cdot 10^{-5}\%$
91	533,332,642	0.0039%	0.0037%
92	1,599,996,811	0.0049%	0.0043%

Table 3.7: First-level subsequence sizes for *Crush* tests with *constant* sizes.

ID	bytes	ID	bytes	ID	bytes
1	2,000,000,000	37	2,000,000,000	67	680,000,000
2	1,200,000,000	38	2,000,000,000	68	400,000,000
3	400,000,000	39	2,600,000,000	69	668,000,000
4	400,000,000	40	2,600,000,000	70	400,000,000
5	400,000,000	41	2,000,000,000	71	480,000
6	400,000,000	42	2,000,000,000	72	480,000
7	400,000,000	43	800,000,000	73	44,739,280
8	400,000,000	44	1,200,000,000	74	109,400,000
9	400,000,000	45	400,000,000	75	327,800,000
10	400,000,000	46	1,200,000,000	76	1,333,336,000
11	800,000,000	47	800,000,000	77	1,200,002,400
12	1,200,000,000	48	2,000,000,000	78	1,200,000,000
13	1,600,000,000	49	820,000,000	79	1,200,000,000
14	1,680,000,000	50	880,000,000	80	1,333,360,000
15	1,680,000,000	51	2,048,000,000	81	1,200,000,000
16	1,920,000,000	52	2,048,000,000	82	2,000,000,000
17	1,920,000,000	53	2,048,000,000	83	2,000,000,000
18	160,000,000	54	2,048,000,000	84	1,600,000,000
19	240,000,000	56	480,000,000	85	2,400,000,000
20	280,000,000	57	1,440,000,000	86	2,400,000,000
21	128,000,000	58	600,000,000	87	2,400,000,000
22	128,000,000	59	1,800,000,000	88	2,400,000,000
23	2,560,000,000	60	384,000,000	89	3,200,000,000
24	2,560,000,000	61	1,152,000,000	90	960,000,000
25	2,560,000,000	62	2,400,000,000	93	1,333,333,400
26	2,560,000,000	63	800,000,000	94	2,000,000,020
35	2,000,000,000	65	600,000,000	95	1,333,333,400
36	2,000,000,000	66	360,000,000	96	2,000,000,040

3.1.4 TestU01 Rabbit

All tests in the Rabbit battery are with *configurable* size. The size is configured using the *bit_nb* argument, where the desired size is en-

tered in *bits* and for use is rounded down to closest multiple of 32. The *bit_nb* has no default value, must be at least 500 and *at most bit_nb* bits will be read from the file. [2, p. 152] However, almost half of the tests require bigger *bit_nb* and will not run otherwise. These tests and their required sizes are in Table 3.8. The minims were found and verified experimentally.

Table 3.8: Minimal values of *bit_nb* argument other than default needed to run tests from *Rabbit* battery.

Test ID	minimal <i>bit_nb</i>
9	31,200
10	960
11	960
15	960
16	1,920
17	3,840
21	51,200
22	5,120,000
23	52,428,800
24	960
25	30,720
26	300,480

Tests 6, 7 and 8 read only data with size 2^k ($k \in \mathbb{N}$) *bits*. The possible values of k are different for each test and shown in Table 3.9. [2, p. 124-126] If the *bit_nb* is not power of two, closest lower applicable power of 2 is used. The *bit_nb* still has to be at least 500, even though smaller amount of bits may be used.

Table 3.9: Maximal values of k for Rabbit tests which take data of size 2^k *bits*.

Test ID	maximal k
6	28
7	20
8	26



Figure 3.1: Number of bytes actually read from tested file by Rabbit test 3 for increasing $bit_nb > 3.3 \cdot 10^9$.

The only test with *variable* size from Rabbit battery is 20. It uses around 80 % of data size specified by *bit_nb* argument. Test 5 reads significantly less data than specified. When the *bit_nb* argument specifies that the test should use 10MB of data, the test 5 uses only 3,536 *bytes*. When the test should use 100MB of data, it uses only 8,488 *bytes*.

For some tests there is an *upper bound* of data used for testing. The test will not read more data, even with growing *bit_nb*. Size of the data that are actually read from the file is not constant in such case and fluctuates around *some* values, even when the test should read more data. Examples of real data size fluctuation is at Figure 3.1.

3.2 Time consumption and performance

Another analysis I performed is examination of the tests' runtimes and performance. This may be used to *exempt* tests that would take *unreasonably* long to execute or to detect problems while running the tests (for example when the test execution gets stuck on non-random data).

Because the runtimes highly depend on used machine and the idea is to make relative comparison between the tests only, they are presented in *relative* form compared to the runtime of Diehard 3d Sphere (Minimum Distance) Test from Dieharder battery (later referred to as *time unit* or *TU*).¹

1. Running on Intel Core i7-1065G7 CPU under Ubuntu 22.04.1 WSL on Windows 10 this test took 0.021 seconds.

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To compare performance of the tests, *throughput* was chosen as a measure. It is presented alongside the runtime. The throughput is calculated as kilobytes² of data processed per time unit.

The used implementations of batteries are taken from RTT (available from [15]). The batteries were run directly (i.e. not using RTT) and each individual test was executed in separate at least one hundred times. Mean runtime over these runs is presented in this Section.

The runtimes and throughputs for Dieharder are in Table 3.10. The Dieharder tests were run without the *rate* option and with default values of *tsample* argument. Runtimes and throughputs for TestU01 SmallCrush and Crush batteries are in Table 3.13 and Table 3.14.

To measure runtimes of test with *configurable* size, I had to fix the first-level subsequence size for each test. For NIST STS battery, I set *stream size* argument to 1,000,000 (the subsequences were 250,000 bytes long). This is the lowest value which satisfies subsequence size recommendations for all the tests. [1] NIST STS runtimes and throughputs are shown in Table 3.12.

For TestU01 Rabbit, Alphabit and BlockAlphabit batteries, I fixed the *bit_nb* argument to value 52,428,800 (the subsequences should be 6,553,600 bytes long). This is the lowest value for which all tests from the three batteries are executed (see Subsection 3.1.4). The runtimes and throughputs for Rabbit battery are in Table 3.15. Alphabit and BlockAlphabit batteries share Table 3.16, because both batteries employ the *same* tests and no difference in runtimes was observed.

2. 1024 bytes

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Table 3.10: Runtimes for and throughputs Dieharder battery tests without variants.

ID	runtime (TU)	Throughput (kB/TU)	ID	runtime (TU)	Throughput (kB/TU)
0	0.43	347	14	$3.03 \cdot 10^{-5}$	25598
1	2.93	1332	15	0.25	1585
2	9.28	539	16	2.86	1846
3	2.10	1116	17	75.79	1031
4	0.91	1126	100	0.19	2024
5	4.79	1710	101	2.73	143
6	33.36	164	102	4.29	91
7	10.01	256	204	0.06	604
8	0.21	1208	205	311.59	1926
9	2.86	1751	206	44.78	1117
10	0.73	128	207	272.13	1622
11	0.27	236	208	180.61	632
12	1.00	47	209	266.52	953
13	5.70	1581			

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Table 3.11: Runtimes and throughputs for Dieharder battery tests with variants.

ID	ntup	runtime (TU)	Through put (kB/TU)	ID	ntup	runtime (TU)	Through put (kB/TU)
200	1	1.18	662	203	7	16.04	1948
200	2	1.59	983	203	8	17.64	1993
200	3	1.89	1238	203	9	19.59	1994
200	4	2.30	1359	203	10	21.24	2023
200	5	3.02	1295	203	11	23.44	2000
200	6	4.20	1116	203	12	25.24	2012
200	7	5.98	915	203	13	27.15	2014
200	8	7.06	885	203	14	29.19	2008
200	9	8.90	790	203	15	30.76	2032
200	10	11.40	685	203	16	32.89	2019
200	11	15.90	540	203	17	35.10	2003
200	12	24.84	377	203	18	36.79	2017
201	2	0.28	279	203	19	38.98	2004
201	3	0.34	347	203	20	40.36	2032
201	4	0.50	310	203	21	42.82	2007
201	5	0.87	225	203	22	44.86	2003
202	2	0.47	1666	203	23	46.18	2030
202	3	0.74	1590	203	24	49.11	1989
202	4	1.09	1436	203	25	50.01	2031
202	5	1.89	1033	203	26	51.24	2058
203	0	2.00	1956	203	27	55.30	1978
203	1	3.86	2025	203	28	57.85	1958
203	2	5.88	1994	203	29	58.84	1992
203	3	7.70	2030	203	30	61.32	1975
203	4	9.90	1973	203	31	64.50	1938
203	5	11.67	2009	203	32	65.41	1971
203	6	13.63	2006				

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Table 3.12: Runtimes and throughputs for NIST STS battery with *stream size* 1,000,000 bits.

Test ID	runtime (TU)	throughput (kB/TU)
1	0.16	782
2	0.17	716
3	0.16	765
4	0.19	658
5	0.17	711
6	0.24	500
7	5.79	21
8	0.77	158
9	0.20	597
10	0.22	560
11	0.22	561
12	0.43	283
13	0.39	314
14	0.93	132
15	1.55	79

Table 3.13: Runtimes and throughputs for TestU01 SmallCrush battery.

Test ID	Runtime (TU)	Throughput (kB/TU)
1	49.20	794
2	36.48	1071
3	16.21	12361
4	16.74	5973
5	13.03	7402
6	17.24	2719
7	12.94	15451
8	16.07	1750
9	22.76	5149
10	25.56	764

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Table 3.14: Runtime and throughputs for TestU01 *Crush* battery.

ID	time (TU)	thr kb/ TU	ID	time (TU)	thr kb/ TU	ID	time (TU)	thr kb/ TU
1	691.72	2824	33	249.16	20070	65	843.17	695
2	412.71	2839	34	310.39	16108	66	207.06	1698
3	706.53	553	35	210.76	9267	67	682.89	972
4	744.61	525	36	277.00	7051	68	177.12	2205
5	1001.45	390	37	685.43	2849	69	581.06	1123
6	1014.13	385	38	694.09	2814	70	157.27	2484
7	1046.35	373	39	1217.74	2085	71	522.24	1
8	1033.21	378	40	1261.90	2012	72	518.17	1
9	995.59	392	41	802.82	2433	73	632.92	69
10	1005.83	388	42	474.13	4119	74	561.55	190
11	960.15	814	43	115.48	6765	75	599.53	534
12	972.95	1204	44	131.44	8916	76	2024.52	643
13	1001.15	1561	45	80.57	4848	77	708.19	1655
14	644.60	2545	46	128.67	9108	78	599.47	1955
15	675.67	2428	47	157.27	4968	79	371.55	3154
16	651.24	2879	48	146.23	13356	80	335.88	3877
17	644.66	2908	49	239.32	3346	81	221.70	5286
18	296.66	527	50	82.72	10389	82	544.90	3584
19	408.85	573	51	101.95	19618	83	521.43	3746
20	763.62	358	52	131.29	15233	84	401.77	3889
21	290.98	430	53	147.27	13580	85	648.33	3615
22	249.12	502	54	152.78	13090	86	486.71	4815
23	356.42	7014	55	109.68	14721	87	642.08	3650
24	418.57	5973	56	770.92	608	88	478.61	4897
25	340.36	7345	57	808.59	1739	89	835.60	3740
26	414.22	6035	58	1164.27	503	90	184.36	5085
27	175.32	7427	59	1379.70	1274	91	796.39	654
28	210.22	6194	60	1567.96	239	92	952.65	1640
29	217.71	8858	61	2014.98	558	93	540.12	2411
30	256.83	7508	62	164.67	14233	94	659.61	2961
31	227.35	13745	63	513.08	1523	95	447.90	2907
32	288.64	10827	64	148.90	2099	96	527.98	3699

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Table 3.15: Runtimes and throughputs for TestU01 Rabbit battery with *bit_nb* 52,428,800

ID	runtime (TU)	throughput kb/TU	ID	runtime (TU)	throughput kb/TU
1	448.60	14	14	2.16	2964
2	16.52	387	15	2.60	2458
3	11.68	548	16	2.10	3053
4	1.59	4019	17	2.17	2953
5	20.32	0	18	3.01	2129
6	70.27	58	19	3.00	2136
7	2.57	50	20	8.55	599
8	20.29	315	21	10.62	603
9	10.62	603	22	13.26	483
10	3.62	1769	23	22.71	282
11	2.14	2988	24	9.26	691
12	2.07	3091	25	7.02	912
13	2.04	3143	26	6.08	1052

Table 3.16: Runtimes and throughputs for TestU01 Alphabit and Block-Alphabit batteries with *bit_nb* 52,428,800.

Test ID	Runtime (TU)	Throughput kb/TU
1	3.49	1835
2	3.51	1825
3	3.36	1902
4	5.72	1119
5	2.60	2459
6	2.11	3034
7	2.06	3109
8	10.52	608
9	8.07	793

3.3 Configuration Calculator

appendix examples, git link (when ready)

The information collected in Sections 3.1 and 3.2 were used in the *Configuration Calculator*. I created this tool to automate creation of battery configuration files for *RTT*. Configuration Calculator supports all batteries that are present in *RTT* except the TestU01 BigCrush battery.

3.3.1 Batteries configurations

The configurations are created based on the length of the tested data. Number of first-level subsequences for each individual test is set so that the test will use as much data as possible without *file rewind*.

For tests with *configurable size*, the default values were chosen the same as in Section 3.2. For NIST STS the *stream size* is set to 1,000,000 *bits* and for TestU01 Rabbit, Alphabit and BlockAlphabit, the *bit_nb* is set to 52,428,800 *bits*. The user may choose their own value for these arguments.

For all individual test the number of first-level tests is calculated as $\lfloor \text{tested file size} \div \text{first-level subsequence size} \rfloor$. For tests with *constant size*, the direct subsequence size is used. For tests with *variable size* the fluctuation of first-level sequence sizes has to be taken into account to prevent *file rewinds*. To achieve this, mean first-level subsequence size increased by a buffer is used as the subsequence size. The buffer size was chosen to be 1% of the subsequence size for tests from TestU01 batteries and 0.1% for tests from Dieharder. Based on analysis from Section 3.1, this should be enough to prevent file rewinds caused by the size fluctuation.

In total 7 tests are always omitted by the Configuration Calculator. Tests 5, 6, 7 and 14 from Dieharder battery are skipped because they are marked as 'Do Not Use' or 'Suspect' by Dieharder. From Crush battery tests 71 and 72 were removed due to their low performance (see Table 3.14). Running each of the two tests would take 12 times longer than running *all* of the remaining tests. The test 5 from Rabbit was also omitted due to low performance (see Table 3.15).

3.3.2 Output Format

Format of the configuration files created by the Configuration Calculator is extension of the original format used by *RTT* (described in Subsection 2.2.1). It contains no new *functional* fields, only information for the user. First such field is *omitted-tests* inside *battery-settings* – tests that will not be run. Either because the tested file is too small for them or because they were removed by default.

Second new field is *battery-defaults*. It contains default argument settings for a given battery and default settings for each individual test, along with the test name and used first-level subsequence sizes. Both *battery-settings* and *battery-defaults* contain also comments for some individual tests with information about why the test was omitted or warning that a given test is with *variable* size.

3.4 P-values uniformity

As was mentioned in Section 1.3, crucial part of two-level testing is examination of observed first-level p-values distribution. The expected theoretical distribution is uniform on interval $(0,1]$. [5, p. 14] Due to various reasons, the real distribution (under the null-hypothesis) may differ from the uniform distribution. This may lead to flawed results of second-level tests. In this section, reasons why this happens are presented along examples of real observed distributions of first-level p-values. It is not goal of this thesis to fix the problem, only to note it.

In the following text, some examples of tests with non-uniform distributions are presented. The data for real distributions were acquired by repeatedly generating files with 5GB of random data using the AES³ with known key as random number generator. Each file was tested using the *RTT* with battery configuration generated by the Configuration Calculator. TODO: CITE UNRELEASED PAPER

The reason why non-uniform distributions are observed is that the distributions of test statistic values in first-level tests are usually approximated in the calculation. This is usually done because the real distribution is known only asymptotically or because it is more efficient. Also, the distribution of test statistic values (and therefore

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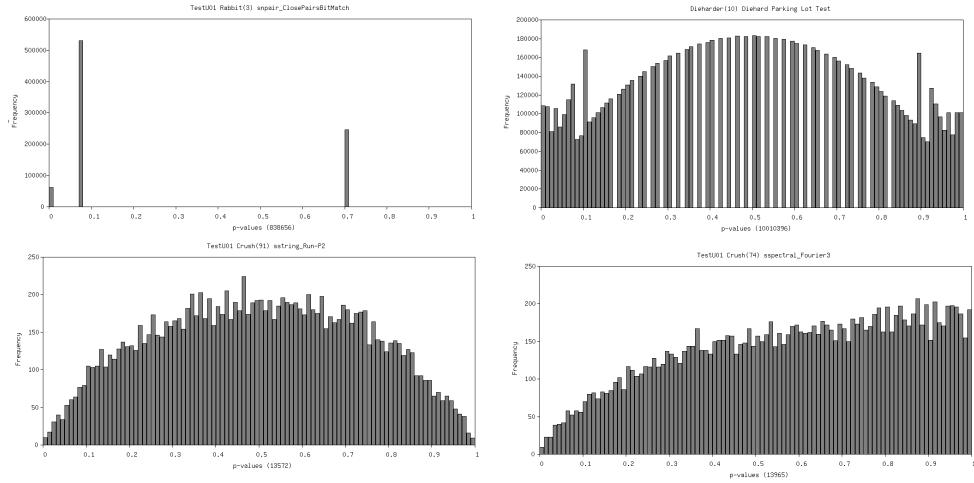


Figure 3.2: Histograms for example of first-level p-values distributions.

p-values), for a fixed sample size, is in fact discrete, but a continuous distribution is often used as approximation to calculate the p-value. This causes error, which accumulates alongside the error caused by limited-precision calculations. [5, p. 7]

Possible outcomes of previous situations are non-uniform distributions of the first-level p-values. The first situation are discrete distributions with *low* number of possible p-values. The most extreme are distributions with only *a few* possible p-values, for example the Rabbit 3 test, in which only six different p-values were observed over the course of almost 840,000 runs . The less extreme tests have lower hundreds of possible first-level p-values, for example the Dieharder 10 test, which produced 221 different p-values over 10,000,000 runs.

More common are tests with high number of observed p-values, but non-uniform distribution. The real distributions are usually *close* to the uniform distribution, but differ in tails (values in tail are significantly more or less probable). Examples of all described flawed distributions can be seen in Figure 3.2.

4 Implementations comparison

The *rtt-py* is supposed to be a newer version of *RTT* and might replace it in the future. Therefore, in this chapter I focus mainly on finding differences between the two. The first section aims at comparing outputs of both testing toolkits. In the second section I am at finding functional differences between them, especially the features they are present in *RTT* and not in *rtt-py*. In the last section I present general suggestions for further improvement of both *RTT* and *rtt-py*.

4.1 Output

? add info about parsing ?

First difference in output between *RTT* and *rtt-py* is the format of the output. *RTT* offers reports only in plaintext format, which contains all of the reported information (see Subsection 2.2.1). The format is human-readable, but hard to navigate. Computer processing requires rather complicated parsing.

The *rtt-py* offers an overview table in HTML and CSV formats, which are both human-readable and useful for quick assessment of the result of the tests. The CSV format is also easily computer-readable. The full HTML format offers more information, usually regarding the test settings. TODO: New info for result assessment In the NIST STS, the proportion of sequences passing the first-level test is added. In the TestU01 batteries, corresponding test statistics values are part of the HTML report as well.

The main functional difference in output between *RTT* and *rtt-py* are the reported information. For this comparison, the full HTML report from *rtt-py* is taken. Both toolkits report the resulting second-level p-values for Dieharder and both the second-level p-value and proportion of sequences passing the first-level test for NIST STS batteries. However, unlike *RTT*, the *rtt-py* does not report first-level p-values, which could be useful for deeper assessment of the results. The *RTT* also reports more information regarding the details about individual tests from NIST STS battery.

For the TestU01 batteries, which employ only repeated single-level tests, the reported information are the same for both toolkits. However, in *RTT* report, repetitions of the same individual test are grouped together and their respective p-values are printed together. In *rtt-py*, each repetition is treated as a separate individual test. The p-values are printed, but the user has to manually group the tests by their names. This is important, because the TestU01 does not perform the two-level test and if the user wishes to apply it, they have to do so on their own. Both toolkits also report additional details regarding the individual test.

4.2 Missing Features of *rtt-py*

One of the problems that need to be addressed is that the *rtt-py* ignores errors and warnings from tests. The most notable example why this is a problem are the *file rewinds*.

In this case, the test will read some parts of the data more than once and inform the user about this situation on the error output. The test will still produce result, which will, however, be biased by repeated parts of the tested file.

This may lead to incorrect interpretation of the results and to Type I or II error. Since the *rtt-py* ignores this, there is no way for the user to be informed about this situation.

As was mentioned in previous section, unlike *RTT*, the *rtt-py* does not report first-level p-values from Dieharder and NIST STS. The first-level p-values can be useful for deeper examination of the tests results.

Batteries from the *TestU01 Crush* family are not run by the *rtt-py*. However, the program options suggest that the batteries are contained. Also, the *rtt-py* ignores the *test-specific-settings* field from the battery configuration files for TestU01 Rabbit, Alphabit and BlockAlphabit batteries.

4.3 Proposed improvements

First proposed improvement for both *RTT* and *rtt-py* is better way to configure the batteries. While *RTT* offers some prepared configuration

4. IMPLEMENTATIONS COMPARISON

files, they are not available for all file sizes. Also, some of the configuration files contained configurations that resulted in *file rewinds* or the tests read less data than was possible, resulting in testing only a part of the file. I implemented this improvement in the form of Configuration Calculator (see Subsection 3.3).

Second proposed improvement are better second level-tests. As is shown in Subsection 3.4, p-values of many first-level tests do not follow the uniform distribution. The improved second-level tests should take these non-uniform distributions into account and compare the observed distributions to the real distributions of the tests. The improved second-level tests also should provide second-level assessment of the TestU01 batteries.

Third proposed improvement is to extend the output format of RTT to computer-readable format, possibly using JSON format as in configurations. This could be used not only for quick computer-made results assessments, but also for the custom second-level tests.

5 Conclusion

A Batteries output examples

A.1 Dieharder

```
#=====
#          dieharder version 3.31.1 Copyright 2003 Robert G. Brown      #
#=====
#   rng_name    |      filename           |rands/second|
#   file_input_raw|              <tested file>| 1.98e+07 |
#=====
#   test_name    |ntup| tsamples |psamples| p-value |Assessment
#=====
```

test_name	ntup	tsamples	psamples	p-value	Assessment
diehard_birthdays	0	100	100	0.83818462	PASSED
diehard_operm5	0	1000000	100	0.91218248	PASSED
diehard_rank_32x32	0	40000	100	0.74062573	PASSED
diehard_rank_6x8	0	100000	100	0.72202153	PASSED
diehard_bitstream	0	2097152	100	0.54621918	PASSED
diehard_opso	0	2097152	100	0.96877577	PASSED
diehard_oqso	0	2097152	100	0.64303740	PASSED
diehard_dna	0	2097152	100	0.64407925	PASSED
diehard_count_1s_str	0	256000	100	0.37839401	PASSED
diehard_count_1s_byt	0	256000	100	0.09580878	PASSED
diehard_parking_lot	0	12000	100	0.33358085	PASSED
diehard_2dsphere	2	8000	100	0.93274571	PASSED
diehard_3dsphere	3	4000	100	0.08383126	PASSED
diehard_squeeze	0	100000	100	0.97500761	PASSED
diehard_sums	0	100	100	0.62861437	PASSED
diehard_runs	0	100000	100	0.45829724	PASSED
diehard_runs	0	100000	100	0.02341244	PASSED
diehard_craps	0	200000	100	0.78964194	PASSED
diehard_craps	0	200000	100	0.90416388	PASSED
marsaglia_tsang_gcd	0	10000000	100	0.93600147	PASSED
marsaglia_tsang_gcd	0	10000000	100	0.79305849	PASSED
sts_monobit	1	100000	100	0.68009432	PASSED
sts_runs	2	100000	100	0.18224901	PASSED
sts_serial	1	100000	100	0.84229425	PASSED
sts_serial	2	100000	100	0.75720963	PASSED
sts_serial	3	100000	100	0.84291363	PASSED
sts_serial	3	100000	100	0.96460124	PASSED
sts_serial	4	100000	100	0.91202326	PASSED
sts_serial	4	100000	100	0.97759751	PASSED
sts_serial	5	100000	100	0.22260482	PASSED
sts_serial	5	100000	100	0.28835866	PASSED

Figure A.1: Example of results table from the *Dieharder* battery.

A. BATTERIES OUTPUT EXAMPLES

```
#=====#
#          Values of test p-values      #
#=====#
|0.04369416|
|0.04827681|
|0.05784669|
|0.06688939|
|0.07899242|
|0.08939748|
|0.09554753|
|0.10181189|
|0.11226737|
|0.11663826|
|0.12257360|
|0.12304411|
|0.12414260|
|0.13178605|
|0.13699214|
.
.
.
|0.95590312|
|0.95849805|
|0.96228421|
|0.97049026|
|0.97974257|
|0.98378624|
|0.98427673|
|0.98622772|
|0.99085826|
#=====#
```

Figure A.2: Examples of first-level p-values printout from *Dieharder* battery

A. BATTERIES OUTPUT EXAMPLES

A.2 NIST STS output

RESULTS FOR THE UNIFORMITY OF P-VALUES AND THE PROPORTION OF PASSING SEQUENCES												
generator is <tested file>												
C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	P-VALUE	PROPORTION	STATISTICAL TEST
33	21	29	26	33	33	40	40	24	21	0.098526	0.9900	Frequency
33	27	28	27	23	32	25	45	29	31	0.262249	1.0000	BlockFrequency
25	36	29	27	25	34	31	29	32	32	0.906970	0.9900	CumulativeSums
32	26	20	35	36	27	29	39	28	28	0.407091	0.9900	CumulativeSums
35	35	25	32	34	30	27	25	25	32	0.810470	0.9967	Runs
24	32	32	34	24	35	23	34	33	29	0.685579	0.9867	LongestRun
23	37	39	19	29	37	26	32	27	31	0.178278	0.9967	Rank
35	22	31	27	34	27	28	31	33	32	0.856907	0.9900	FFT
43	24	33	28	30	30	33	24	29	26	0.407091	0.9833	Universal
28	33	29	28	27	26	40	24	32	33	0.699313	0.9900	ApproximateEntropy
.												
.												
22	27	17	11	17	19	19	16	21	19	0.427082	0.9894	RandomExcursions
23	17	23	24	21	15	18	19	14	14	0.568055	0.9947	RandomExcursions
12	20	15	15	17	21	28	21	21	18	0.324180	0.9947	RandomExcursions
22	29	10	16	18	14	25	16	21	17	0.071670	0.9840	RandomExcursions
19	17	15	24	23	16	15	16	25	18	0.568055	0.9787	RandomExcursions
17	18	18	24	24	8	20	18	18	23	0.260784	1.0000	RandomExcursions
15	21	19	23	19	24	18	13	23	13	0.468595	0.9947	RandomExcursions
19	18	14	23	23	15	17	23	17	19	0.761937	0.9947	RandomExcursions
35	35	23	31	30	29	35	34	28	20	0.514124	0.9933	Serial
33	32	39	29	30	28	27	33	28	21	0.664861	1.0000	Serial
39	26	30	23	30	29	40	28	23	32	0.339799	0.9867	LinearComplexity

The minimum pass rate for each statistical test with the exception of the random excursion (variant) test is approximately = 0.975064 for a sample size = 300 binary sequences.

The minimum pass rate for the random excursion (variant) test is approximately 0.971133 for a sample size = 188 binary sequences.

For further guidelines construct a probability table using the MAPLE program provided in the addendum section of the documentation.

Figure A.3: Example of results table from the *NIST STS* battery.

A. BATTERIES OUTPUT EXAMPLES

```
FREQUENCY TEST
-----
COMPUTATIONAL INFORMATION:
-----
(a) The nth partial sum = -852
(b) S_n/n           = -0.000852
-----
SUCCESS          p_value = 0.394214

FREQUENCY TEST
-----
COMPUTATIONAL INFORMATION:
-----
(a) The nth partial sum = 1036
(b) S_n/n           = 0.001036
-----
SUCCESS          p_value = 0.300202

FREQUENCY TEST
-----
COMPUTATIONAL INFORMATION:
-----
(a) The nth partial sum = 102
(b) S_n/n           = 0.000102
-----
SUCCESS          p_value = 0.918757

.
.
.

FREQUENCY TEST
-----
COMPUTATIONAL INFORMATION:
-----
(a) The nth partial sum = -612
(b) S_n/n           = -0.000612
-----
SUCCESS          p_value = 0.540538
```

Figure A.4: Example of p-values, test statistics and other information from NIST STS's *stats.txt* file.

A. BATTERIES OUTPUT EXAMPLES

A.3 TestU01 output

A.4 FIPS battery output

```
{  
    "accepted": false,  
    "sequence": <tested file>,  
    "tests": [  
        {  
            "name": "FIPS 140-2(2001-10-10) Monobit",  
            "num_failures": 1,  
            "num_runs": 2000  
        },  
        {  
            "name": "FIPS 140-2(2001-10-10) Poker",  
            "num_failures": 0,  
            "num_runs": 2000  
        },  
        {  
            "name": "FIPS 140-2(2001-10-10) Runs",  
            "num_failures": 0,  
            "num_runs": 2000  
        },  
        {  
            "name": "FIPS 140-2(2001-10-10) Long run",  
            "num_failures": 0,  
            "num_runs": 2000  
        },  
        {  
            "name": "FIPS 140-2(2001-10-10) Continuous run",  
            "num_failures": 0,  
            "num_runs": 2000  
        }  
    ]  
}
```

Figure A.5: Example of output from *FIPS* battery.

A.5 BSI battery output

```
{  
    "sequence": <tested file>,  
    "tests": [  
        {  
            "error": false,  
            "name": "T0 - Words",  
            "num_failures": 0,  
            "num_runs": 127  
        },  
        {  
            "error": false,  
            "name": "T1 - Monobit",  
            "num_failures": 0,  
            "num_runs": 257  
        },  
        {  
            "error": false,  
            "name": "T2 - Poker",  
            "num_failures": 0,  
            "num_runs": 257  
        },  
        {  
            "error": false,  
            "name": "T6 - Uniform Distribution",  
            "num_failures": 4000,  
            "num_runs": 4000  
        },  
        {  
            "error": false,  
            "name": "T7 - Homogeneity",  
            "num_failures": 0,  
            "num_runs": 83  
        },  
        {  
            "error": false,  
            "name": "T8 - Entropy",  
            "num_failures": 0,  
            "num_runs": 193  
        }  
    ]  
}
```

Figure A.6: Example of output from *BSI* battery.

B Testing Toolkits

B.1 RTT settings

```
{
    "toolkit-settings": {
        "logger": {
            "dir-prefix": "results/logs",
            "run-log-dir": "run-logs",
            "dieharder-dir": "dieharder",
            "niststs-dir": "niststs",
            "tu01-smallcrush-dir": "testu01/smallcrush",
            "tu01-crush-dir": "testu01/crush",
            "tu01-bigcrush-dir": "testu01/bigcrush",
            "tu01-rabbit-dir": "testu01/rabbit",
            "tu01-alphabit-dir": "testu01/alphabit",
            "tu01-blockalphabit-dir": "testu01/blockalphabit"
        },
        "result-storage": {
            "file": {
                "main-file": "results/testbed-table.txt",
                "dir-prefix": "results/reports",
                "dieharder-dir": "dieharder",
                "niststs-dir": "niststs",
                "tu01-smallcrush-dir": "testu01/smallcrush",
                "tu01-crush-dir": "testu01/crush",
                "tu01-bigcrush-dir": "testu01/bigcrush",
                "tu01-rabbit-dir": "testu01/rabbit",
                "tu01-alphabit-dir": "testu01/alphabit",
                "tu01-blockalphabit-dir": "testu01/blockalphabit"
            },
            "mysql-db": { // Database storage does not have to be filled,
                           // because it is optional functionality.
                "address": "",
                "name": "",
                "port": "",
                "credentials-file": ""
            }
        },
        "binaries": { // Paths to executables of test batteries. Only
                       // this setting has to be filled in by the user.
            "niststs": "/rtt-statistical-batteries/niststs",
            "dieharder": "/rtt-statistical-batteries/dieharder",
            "testu01": "/rtt-statistical-batteries/testu01"
        },
        "miscellaneous": {
            "niststs": {
                "main-result-dir": "experiments/AlgorithmTesting/"
            }
        },
        "execution": {
            "max-parallel-tests": 8,
            "test-timeout-seconds": 40000
        }
    }
}
```

Figure B.1: General settings for RTT stored in *rtt-settings.json* file.

B.2 RTT battery configuration

```
{
  "randomness-testing-toolkit": {
    "dieharder-settings": {
      "defaults": { // Default settings for all tests in the
        "test-ids": [ // battery including IDs of tests to be
          "0-4", // executed
          "200-204"
        ],
        "psamples": 100
      },
      "test-specific-settings": [ // List of tests with settings different
        { // from defaults or tests with variants
          "test-id": 2,
          "psamples": 81
        },
        {
          "test-id": 200,
          "variants": [ // List of all test variants to be executed
            { // for a given test
              "arguments": "-n 1",
              "psamples": 100
            },
            {
              "arguments": "-n 2",
              "psamples": 100
            }
          ]
        }
      ],
      "nist-sts-settings": { // Settings for next battery
        ...
      }
    }
  }
}
```

Figure B.2: Example of battery configuration file for *RTT*.

C RTT output

D rtt-py out

Bibliography

1. BASSHAM III, Lawrence E; RUKHIN, Andrew L; SOTO, Juan; NECHVATAL, James R; SMID, Miles E; BARKER, Elaine B; LEIGH, Stefan D; LEVENSON, Mark; VANGEL, Mark; BANKS, David L, et al. *SP 800-22 rev. 1a. a statistical test suite for random and pseudorandom number generators for cryptographic applications.* National Institute of Standards & Technology, 2010. Available also from: <https://csrc.nist.gov/Projects/random-bit-generation/Documentation-and-Software>.
2. L'ECUYER, Pierre; SIMARD, Richard. *TestU01 - A Software Library in ANSI C for Empirical Testing of Random Number Generators - User's guide, compact version.* 2002. Available also from: <http://simul.iro.umontreal.ca/testu01/guideshorttestu01.pdf>.
3. MOORE, David S.; NOTZ, William I. *The Basic Practice of Statistics.* Macmillan Learning, 2021. ISBN 1-319-38368-8.
4. L'ECUYER, Pierre; SIMARD, Richard. TestU01: A C library for empirical testing of random number generators. *ACM Transactions on Mathematical Software (TOMS).* 2007, vol. 33, no. 4, pp. 1–40.
5. SÝS, Marek; OBRÁTIL, Lubomír; MATYÁŠ, Vashek; KLINEC, Dušan. A Bad Day to Die Hard: Correcting the Dieharder Battery. *Journal of Cryptology.* 2022, vol. 35, pp. 1–20.
6. D'AGOSTINO, Ralph B.; STEPHENS, Michael A. *Goodness-of-Fit Techniques.* Routledge, 1986. ISBN 0-8247-8705-6.
7. SHESKIN, David J. Parametric and nonparametric statistical procedures. Boca Raton: CRC. 2000.
8. *Robert G. Brown's General Tools Page* [online]. Brown, Robert G. [visited on 2023-11-10]. Available from: <https://webhome.phy.duke.edu/~rgb/General/dieharder.php>.

BIBLIOGRAPHY

9. VAVERČÁK, Patrik. *Aplikácia na štatistické testovanie pseudonáhodných postupností*. Bratislava, 2022. Available also from: <https://opac.crzp.sk/?fn=detailBiblioFormChildEBUS6&sid=D9F0BB0A8DA9926980A890D31B33&seo=CRZP-detail-kniha>. Master's thesis. Slovak University of Technology in Bratislava, Faculty of Electrical Engineering. Supervised by Matúš JÓKAY.
10. EDDELBUETTEL, Dirk. *eddelbuettel/dieharder* [online]. [visited on 2023-11-21]. Available from: <https://github.com/eddelbuettel/dieharder>.
11. *Random Bit Generation | CSRC* [online]. [visited on 2023-11-10]. Available from: <https://csrc.nist.gov/projects/random-bit-generation/documentation-and-software>.
12. SÝS, Marek; ŘÍHA, Zdeněk. Faster randomness testing with the NIST statistical test suite. In: *Security, Privacy, and Applied Cryptography Engineering: 4th International Conference, SPACE 2014, Pune, India, October 18-22, 2014. Proceedings 4*. Springer, 2014, pp. 272–284.
13. SÝS, Marek. *sysox/NIST-STS-optimised* [online]. [visited on 2023-11-21]. Available from: <https://github.com/sysox/NIST-STS-optimised>.
14. *Empirical Testing of Random Number Generators* [online]. [visited on 2023-11-12]. Available from: <http://simul.iro.umontreal.ca/testu01/tu01.html>.
15. *rtt-statistical-batteries* [online]. [visited on 2023-11-10]. Available from: <https://github.com/crocs-muni/rtt-statistical-batteries>.
16. NIST. *SECURITY REQUIREMENTS FOR CRYPTOGRAPHIC MODULES*. 2001. Available also from: <https://csrc.nist.gov/pubs/fips/140-2/upd2/final>.
17. VAVERČÁK, Patrik. *rtt-statistical-batteries* [online]. [visited on 2023-11-13]. Available from: <https://github.com/pvavercak/rtt-statistical-batteries>.

BIBLIOGRAPHY

18. MORAES HOL SCHUH, Henrique de. *fips.c · master · Henrique de Moraes Holschuh / rng-tools · GitLab* [online]. [visited on 2023-11-13]. Available from: <https://salsa.debian.org/hmh/rng-tools/-/blob/master/fips.c>.
19. KILLMANN, Wolfgang; SCHINDLER, Werner. *A proposal for: Functionality classes and evaluation methodology for true (physical) random number generators.* 2001. Available also from: https://www.bsi.bund.de/SharedDocs/Downloads/DE/BSI/Zertifizierung/Interpretationen/AIS_31_Functionality_classes_evaluation_methodology_for_true_RNG_e.html.
20. OBRÁTIL, Lubomír. *The automated testing of randomness with multiple statistical batteries.* Brno, 2017. Available also from: <https://is.muni.cz/th/uepbs/>. Master's thesis. Masaryk University, Faculty of Informatics. Supervised by Petr ŠVENDA.
21. *crocs-muni/randomness-testing-toolkit: Randomness testing toolkit automates running and evaluating statistical testing batteries* [online]. [visited on 2023-11-14]. Available from: <https://github.com/crocs-muni/randomness-testing-toolkit>.
22. *pvavercak/rtt-py: Randomness testing toolkit in python* [online]. [visited on 2023-11-14]. Available from: <https://github.com/pvavercak/rtt-py>.