# THE JOURNEY OF QUANTUM INFORMATION TECHNOLOGY

## DIE REISE DER QUANTUM INFORMATION TECHNOLOGY

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***Abstract*** — This paper overviews the development of the quantum information technology and the quantum computing over the years, highlighting its potential promising applications in different technological clusters. This paper provides brief description of the quantum computing and the most significant differences with the classical computer systems and technologies. Over 500 different articles, papers and some thesis dissertations in the field of Quantum computing and Quantum algorithms have been reviewed and classified in 8 different technological clusters. Combined together they form the scientific field of Quantum Information Technology.

***Zusammenfassung*** — Dieser Artikel gibt einen berblick ber die Entwicklung der Quanteninformationstechnologie und des Quantencomputers im Laufe der Jahre und beleuchtet die potenziellen vielversprechenden Anwendungen in verschiedenen Technologieclustern. Dieser Artikel bietet eine kurze Beschreibung des Quantencomputers und der wichtigsten Unterschiede zu den klassischen Computersystemen und -technologien. ber 500 verschiedene Artikel, Artikel und einige Dissertationen im Bereich Quantum Computing und Quantum-Algorithmen wurden berprft und in 8 verschiedene technologische Cluster eingeteilt. Zusammen bilden sie das wissenschaftliche Gebiet der Quanteninformationstechnologie.

## I. Introduction.

For source of information for this paper has been used the Cornel University Library and its search engine, which can be found at the following web site: https://arxiv.org Formerly understood only by the physicists, now everybody starts realizing the huge potential of the quantum computing. The quantum computer follows the laws of quantum mechanics - a branch of physics, which unveils how the world works on very low particle level. At so low level, the particles have strange (for ordinary people) behavior ( they act simultaneously as wave and particle), taking one than more states at the same moment of time. Also the particles are acting together even if they are on a very big distance (for the nowadays understandings) one from another. The quantum computing is using these quantum physics laws to create novel, different way of computing and information processing, which is very promising.

In the context of Quantum computing, the convergence between the following technological clusters: Artificial Intelligence, Computational complexity, Cryptography and security, Data structures and algorithms, Emerging technologies, Logic in computer science, Neural and evolutionary computing, System and control (see 1), gives the quantum computing field the ability to grow with very fast speed, especially in the last 10 years, when the technological sector has huge growth impact on the economies of the leading countries in the world.

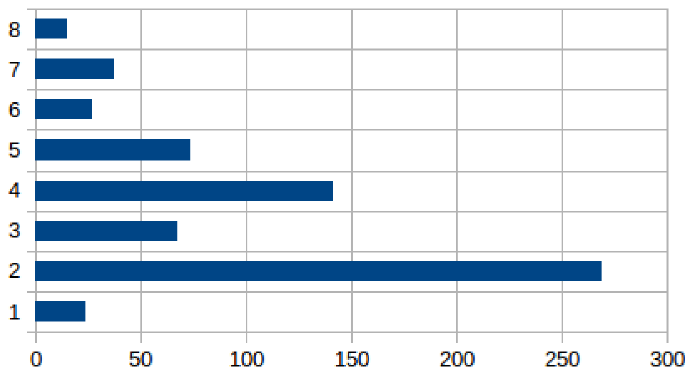


Fig. 1. Number of papers reviewed in the following technological clusters: 1. Artificial Intelligence 2. Computational Complexity 3. Cryptography and Security 4. Data Structures and Algorithms 5. Emerging Technologies 6. Logic in Computer Science 7. Neural and Evolutionary Computing 8. Systems and Control

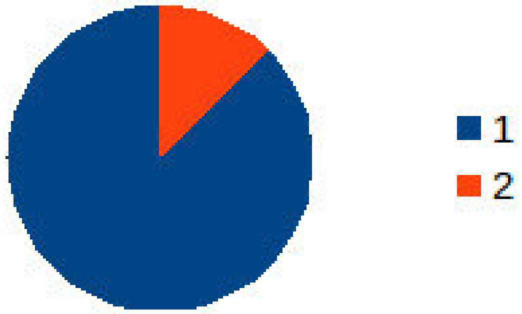


Fig. 2. Papers published in the Artificial Intelligence cluster:
1. In the period 2006-2017
2. In the period 1999-2005

## II. Technological Clusters Development Through The Years.

The development of programmable quantum processors made with silicon has taken a few steps forward for the last few years. The most significant achievement recently is the breakthrough of IBM in development of a quantum computer, which can handle 50 qubits, announced at the IEEE Industry Summit on the Future of Computing in Washington D.C. Asides from the 50 qubit device, IBM have also a 20 and 14 qubit devices, which are available for use through the IBM Q Network. This hardware development gives a push to the software developers and researchers, who want to create algorithms and software running on a quantum processor. As said before, there is a convergence between some technological clusters and the quantum computing, which brings out faster growth in both the technological cluster and the quantum computing area.

## III. Quantum Artificial Intelligence.

The artificial intelligence consists of many different subfields, which makes it extremely interesting and diversified. The traditional problems, which AI solves, include knowledge, reasoning, planning, learning, perception, natural language processing. Even in this century, when the computer processing power has increased incredibly, it is still the limitation for the development of the most complex artificial intelligence systems. Here comes the quantum computing to help with its incredible hypothetical speedup advantage over the classical computer in a certain field [1]–[5], they could be of great help to the researchers.

The first papers (reviewed in the process of writing this article), which investigate the quantum search problem give a solution, which could be applied to highly constrained problems [6]. A big growth of the number of the published papers is noticeable in the last decade (2006-2017). Starting with the context of classical uncertainty combined with the theory of quantum computing, where quantum mechanical dependencies had been described using a novel class of graphical representations, called Markov Entanglement Networks [7], through the application of Markov network in quantum statistical physics [8], clustering [9], reversible boolean circuits synthesys [10], medicine [11], planar graphs [12] and finishing with presentation of new opportunities for optimization algorithms [13], including ising processing units [14], discrete [15], [16], binary [17] etc. From the total amount of 24 papers reviewed, 87.5% have been published in the last decade (see 2), which shows the rising potential of the quantum computers.

## IV. Computational Complexity and Quantum Computing.

The computational complexity theory classifies computational problems according to their inherent difficulty, while the resulting classes are always related to each other. All the computational problems are studied and solved by mathematical models, which require certain amount of resources (time, storage, communication, processing power (number of processors or processor cores), etc. ). With the development of the quantum computing new complexity classes have been defined. These classes use quantum computers and quantum computational models based on quantum mechanics. The two most important quantum complexity classes are BQP (bounded-error quantum polynomial time) and QMA (Quantum Merlin-Arthur, which is the analog of the non-probabilistic complexity class NP.

As seen from Fig.1 this cluster is the biggest among the others reviewed. The models for quantum computing have been developed during the years in many directions, starting with the quantum automata [18]–[24] and going through topics like three size estimation [25], graph connectivity [26], EQUALITY and AND [27], multivariate polynomial interpolation [28], matrix operations [29], graphs [30]–[33] and quantum walk [34].

Undoubtedly this cluster takes the first place in the quantum computing and its development is going to be on the fastest lane and one of the reasons for that is because every algorithm and computational model must be evaluated and classified [35]–[42]. Studying the relationship between classical and quantum complexity classes might start a new competition between the two computing technologies, which might lead to solving harder and harder problems in less time [43]–[138].

The development of quantum algorithms has been on the rise in recent years, with some of the guidelines in which researchers work are Quantum Fourier [128], [139]–[141], Quantum querying [142]–[145], Boolean problems [146]–[148], Quantum rejection sampling [149], Advice coins algorithms [150], Algorithms for QMA-complete problems [151], Tree isomorphism and state symmetrization [152], Quantum separability problems [153], development of algorithms related with NP-Complete, Exact cover and 3SAT problems [34], [94], [154]–[164], Quantum counterfeit coin problems [165], match-gate computations [166], [167], parenthesized testing [168], algorithms for Regulator and Principal ideal problems [169]–[171], algorithms for quantum branching programs [172], classical theorems quantum proofs [173], Shor's algorithm [174]–[177], quantum algorithms for recognition of non-RMM regular languages [178], approximate counting [179], quantum queries [148] quantum algorithms for hidden subgroup problem [180], quantum walk based search algorithms [113], [136], [169], [181], [182].

## V. Quantum Cryptography and Security.

Cryptography guarantees the security between two parties through encryption of the data, while both parties must agree on a common key, which must be kept in secret.

While nowadays this security is based on the mathematical complexity of the cryptographic algorithms, which is supposed to be revolutionized by the quantum computers [183]. Some requirements for the security mechanisms that have been developed in the framework of the INDECT research project have been reviewed in relation with the quantum cryptography [184].

Researchers use the entanglement property of the quantum systems to achieve secure transmission of data [185]–[188]. The quantum mechanics find very useful applications in data transfer systems with oblivious transfer [189], multi-receiver transfer [190]. In data mining and analytics, sensitive data-sets could be preserved using new quantum protocols [191], [192].

A blind quantum computation [193] shows how independent participants can perform computational tasks while holding different resources.

In the recent decade lots of new cryptography algorithms which include both classical and quantum computational systems have been developed, and also existing algorithms have been upgraded, so they could resist on quantum attacks [194]–[229]. Using Simon's quantum algorithm, an insecurity can be shown in symmetric-key primitives [230].

A new quantum encryption scheme is shown in [231], which is based on the solution for the hidden subgroup problem. Sbastien Kunz-Jacques and Paul Jouguet examined the consequences of replacing the MAC with cryptographic hash-based signature algorithm for a Quantum Key Distribution protocol. The Quantum Key Distribution protocol is wild-spread topic in the quantum cryptography [185], [186], [232]–[236].

The homomorphic data encryption enables a new way of processing where the data does not need to be decrypted for computational purposes [200], [237], [238]. This quantum fully homomorphic algorithm is based on universal quantum circuit.

The quantum enigma cipher consists quantum properties in the physical layer, which prevents Brute force attacks. In [238] it is shown that the quantum illumination can be an element of the most simple quantum enigma cipher and make a difference in error performance.

The goal of quantum resistant cryptography algorithms is to develop problems, which are difficult to solve with quantum computers, like Knapsack problem modifications [239], [240]. New embedding techniques have been used for image authentication [241] and efficient code-based crypto systems for embedded platforms [242]. Generating random numbers with very high speed can be achieved by Quantum random number generators [243], [244], which increases the security level of the cryptographic applications. A protocol which is secure against quantum attacks has been gained by using this lattice-based hash and lattice-based commitment scheme [245].

Quantum security is not only limited to cryptographic algorithms and protocols for data transfer, but it looks after other security aspects like the vulnerabilities of the quantum computers when classical or quantum attack attempts have been made [246]–[248].

## VI. Quantum Algorithms and Data Structures.

Quantum algorithms have developed greatly from quantum mechanical systems simulations to applications in wide variety of fields [249]. May be the most widely known application of quantum computing is the factoring [250]. Peter Shor introduces efficient randomized algorithms for the problems of factoring integers and finding discrete logarithms [251]. Shor's algorithm-based applications are shown in [252], [253] and [254]. In Michael Feldmann's paper a polynomial time deterministic factoring algorithm is provided [255]. Essential process of quantum computing systems is the Quantum error correction [256]–[258]. In [259] a pearl-necklace encoder is presented and in [260] the work extends to an algorithm for turning this encoder into a realizable quantum convolutional encoder. Undoubtedly, holding 30% of the papers in this cluster, the topic for quantum search is one of the most promising applications of quantum computers. Starting with the Grover's algorithm for database search [261], which shows the clear advantage over a classical computer for exhaustive search [262]–[269] and how fast quantum search can be [270]. Continues through the years with different applications like single query in large databases [271], search for a needle in a haystack [272], quantum search on structured problems [273], [274], tree search problem [275], [276], quantum search with multiple solutions [277]–[280], partial search [281]–[283], scheduling problem [284], quantum search for a classical object [285], robust search [286], suppressing the transitions of a quantum mechanical system [287], fixed point quantum search [288], [289], quantum searching amidst uncertainty [290], super-linear amplitude amplification [291], quantum algorithm for finding the minimum [292], maze problem [293], symmetry detection [294]. In [295] the authors use the Grover's search algorithm to define goals for recommendation system and apply it for wide range of optimization problems.

Grover also provides a framework for design and analysis of quantum mechanical algorithms in [296], consequence of which is the search algorithm. He shows a new perspective for quantum computing algorithms [297] and describes the quantum search as a resonance phenomena [298].

Tree data structure has a lot of applications mostly because by definition it is hierarchical data structure. The Quantum Transverse Field Ising Model [299] gives a generalization to an infinite tree geometry of iTEBD algorithm. Related interesting application of quantum algorithm for counting subgraphs parametrized by the tree width of a graph has been introduced with Non-commutative Subset Convolution [300]. Regarded as a subclass of quantum annealing, the adiabatic quantum computation does the calculations based on the adiabatic theorem [301]–[316].

Quantum algorithms find a lot of useful application in graph theory [317]–[328], tomography [329]–[332], lattice-related problems [333]–[335], group-related problems [336]–[342], Fourier transform [250], [335], [343], consensus problems [344], matrix problems [345]–[357], encoding [358]–[360], quantum separability problem [361], mean approximation [362], backtracking of one-dimensional cellular automata [363], quantum satisfiability problem [364], linear regression [365], pattern matching [366], Boolean functions influences approximation [367], shortest path prob-

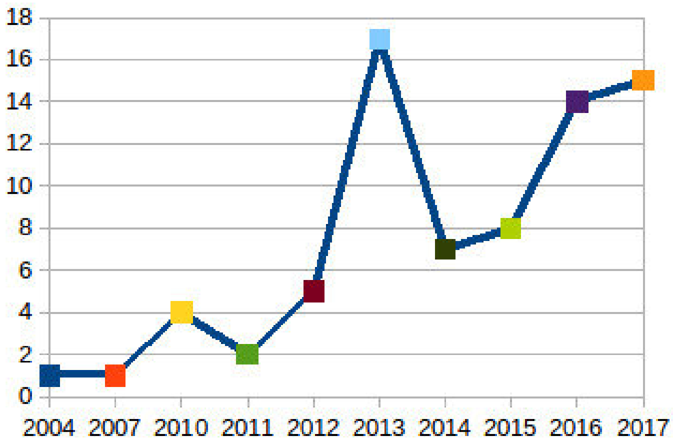


Fig. 3. Distribution of papers published over the years in the Emerging Technology cluster.

lem [368], quantum game theory [369], solving linear systems of equations [370], Markov chains [371], recovering and identity testing [372], hypercube monotonicity testing [373], solitude verification [374], boson sampling [375], DP and LE problems [376]. New type of quantum oracle [377] provides the oracle access to conditional probabilities associated with an underlying distribution.

Quantum walks are counterparts of Markov chains, and as such, have algorithmic applications [378]–[384]. Quantum walk on a graph shows an exponentially fast hitting times over classical counterparts. Such a speed-up has been presented by the quantum search algorithm based on quantum random walk architecture [385]. The quantum walk is used for the construction of an algorithm for element distinctness [386].

## VII. Quantum Computing as Emerging Technology.

Describing quantum computing as emerging technology, we can say it is a generally new, still underdeveloped and has very high growth potential, and also it is capable of changing the status quo. This cluster has more than 10% of the total number of the articles reviewed in this paper. 74 articles have been reviewed, which could describe Quantum computing as emerging technology and more than 75% (60 out of 74) of these articles are published in the the 2013-2017 period [387]–[446], which is proof, that with the development of the technological clusters mentioned above, the Quantum computing can be categorized as fast growing technological field with prominent impact. As seen on 3. there is quite fast growth of the number of articles published in the past several years - while up to 2010 [447]–[460] the average number of articles per year is two, the number is increasing to average of 11 articles per year for the period from 2012 until 2017.

A decade ago when the quantum computing has not been on the fast lane of technological growth, the content of the articles and the focus of the researchers had been connected with the equivalence of the quantum circuits and problems with the simulation of the systems, implementation and real-task examples of well-known algorithms from the 1990s ( Grover's and Shor's algorithms). While later, in the past 5 years, we can see interoperability and integration between the Quantum computing theory and the Classical computing theory, in result of which nowadays there are different platforms [410], [429], frameworks [416], [420], [436], programming languages [400], [454], which are used for description of quantum gates, circuits [415], [460], systems, presenting and performing operations on quantum systems, or quantum computer simulators [428], [459].

## VIII. Logic in Computer Science.

Before the first quantum computer was build for real the quantum algorithms were sequences of abstract operations. In [461] some categorical semantics are presented to help proving some necessary conditions.

There is a certain area of computability in the mathematics and theoretical computer science which consists of problems known to be mathematically non-computable. Determination of the computability not only by mathematics, but also by quantum-physical principles, gives new possibilities for solving these types of problems. There are quantum algorithms which could solve a classically non-computable decision problems like Hilbert's tenth problem or Turing halting problem [462]–[467].

The implementation of every quantum algorithms needs a programming language and modeling the structure of information. In [468] the authors map the theory to the Von Neumann model and to the theory of object-oriented programming. They present a language called Quanta. Alternative model of quantum computation has been developed as quantum lambda calculus [469], [470].

A novel quantum programming paradigm has been introduced in 2014 - the superposition of programs, guaranteed by the universality of quantum walks as a computational model [471]. Using group theory to exploit the properties of some synthesis problems could be achieved by transformation of the problem to multiple-valued optimizations [472]. Since quantum entanglement is one of the key properties of a quantum system and gives a major difference between the classical and quantum computing, it is important to analysis this property deeper [473].

Nondeterministic quantum programs could be represented by sequential quantum Markov chains over the common state space. The steps in these programs are executed nondeterministically in the Hilber space. In [474] the conditions and necessity of the termination of these quantum programs are being presented.

Bi-simulation is an interesting topic in the theoretical computer science, where one of two systems simulates the other and vice versa. In quantum computing to check for bi-simulation, a verification of the bi-similarity of the resultant configuration must be performed. This check could be done either by considering strong bi-simulations or by using symbolic operational semantic at the quantum operation level [475].

Modeling quantum cryptographic protocols faces few challenges, one of which is the cryptographic proof. Although the security is based on the quantum mechanical principles, the design of the quantum protocol is the key element for building secure cryptographic quantum systems. A novel notion of Markov quantum chains has been introduced, where probabilistic computation tree login is defined and model-checking algorithm is developed [476].

## IX. Neural and Evolutionary Computing.

Artificial neural networks (ANN) are the typical and most advanced systems in the artificial intelligence nowadays. The neural networks are artificial representations of human neurons - the constructive parts of the brain. Every ANN is a system of processing units, which are very basic representation of the biological neurons, where every element of the network takes the input signal and calculates some output signal. The output signal is the input for the next elements in the system.

The perceptrons are the basic computational units in ANN and they play an important role in the machine learning. Based on the quantum phase estimation algorithm, a quantum perceptron model is presented in [477]. KAK is a family of neural networks, which are able to learn patterns quickly. Using complex inputs in these networks may give the possibility of their quantum applications [478]. Using the recurrent neural networks for optimization of dynamical decoupling for quantum memory [479] is useful for finding solutions, according to a specific hardware, because of its black box architecture.

Neural networks computations based on Quantum probability have applications in principal subspace analysis [480], where the model is based on two quantum physics concepts - density matrix and Born rule.

Training artificial neural networks requires the determination of suitable neural network architecture. This process is usually achieved empirically, and its automation could be achieved through a learning procedure for a quantum weightless neural network, where the learning algorithm uses the principle of superposition [481]. In the recent years there are new proposals for quantum neural network architecture, like the quantum perception over the field [482], Widrow-Hoff learning rule based model [483], feed-forward neural networks [484].

Sparse distributed representations (SDR) are the way of how the human brain processes information. Few of the many neurons are active at the same time, and the pattern is very significant. The probability amplitude coefficients in quantum superposition might be represented by using SDRs [485]. Deep learning has huge impact on the artificial intelligence recent years. The quantum computing provides more comprehensive framework for deep learning than classical computing. An implementation of quantum training of deep restricted Boltzmann machine has been reviewed in [486], [487]. The evolutionary computing uses algorithms inspired by the mechanisms of the biological evolution ( reproduction, mutation, recombination and selection). Quantum evolutionary programming has mainly two sub-areas - Quantum Inspired Genetic Algorithms (QIGAs) and Quantum Genetic Algorithms (QGAs) [488], [489]. Quantum computing might have a huge impact on computational intelligence. Some paradigms could be implemented as quantum programs [490]. The quantum inspired evolutionary algorithms, such as HQEA, QHW (Remote and local search), QEA, NQEA, AQDE, GSQPO, QIGA2, QPSO, msMS_DE, perform significantly faster than a classical genetic algorithms [491]–[501]. The evolutionary algorithms on Ising spin glass instances defined by Chimera topology are being investigated in [502]. One of the key tasks in the quantum information technologies is the Robust control design.

Multi-Observable Quantum Control is a topic within the chemistry and physics applications of controlling quantum phenomena. In [503] specific systems are considered to be Pareto optimized subject to uncertainty, however one of the concerns is the impact of the fitness disturbance on algorithmic behavior and several theoretical issues have been raised. Network intrusion detection systems are software systems that monitor networks for malicious activities. The improvement of the classification accuracy and malicious detection is achieved by using Bio-Inspired Optimization Algorithms. Using quantum computers can help building new NIDS where the output results outperform the classical approach. In [504] a quantum vaccined immune clonal algorithm with the estimation of distribution algorithm (QVICA-with EDA) is proposed for this task.

## X. Systems and Control.

Control systems are surrounding us in almost any life aspect nowadays. Systems and Control cluster reviewed in this chapter consists of five sub-areas of the control theory field: Robust control, Optimization problems, Entropy, Quantum stochastic systems and Identification. Although, it is a huge research area, the research connected with quantum computing is very limited at the time this paper has been written.

In general robust control is an approach for controller design related with some uncertainties, where the stability of the controlled system is guaranteed together with some level of performance. Quantum computers are still in their early stage, and to meet all the targets for a control design ( stability, disturbance rejection, noise rejection, saturation avoidance, performance), is one of the key tasks in the development of this technology. Sampling-based learning control method is one of the most promising techniques for robust control design [505], [506]. This method includes two steps - training and testing. Performing the training step, the system is conducted using artificial samples generated by sampling uncertainty parameters. Later in the testing step, additional samples are tested for control performance evaluation.

System identification is a process for building mathematical models of complex dynamical systems, based on system's input and output. One of the key applications of the identification process in quantum technology is related with unknown quantum gate [507]. This is a two stages procedure. At the first stage series of pure states are given as an input to the gate. The second stage consists of fast gate tomography on the output states. The data from the tomography is later used for the reconstruction of the quantum gate. One of the fundamental problems in the physics of complex systems is the quantification of the complexity of the network. In [508] it is shown that the network's von Neumann entropy for a quantum network is non-decreasing at the consensus limit. Another interesting correction has been found in this paper regarding quantum gossiping algorithms with deterministic coefficients and classical gossiping algorithms with random coefficients. The transfer function gives the corresponding output value for each possible input value for a control system. When subsystems are connected in series it is also called cascaded. Generic

Linear Quantum stochastic systems have pure cascade realization [509]. This realization finds applications in coherent feedback control and filtering.

Optimization problem is the problem of finding the best solution out of the feasible ones. In quantum technology one of the most important optimization problem is finding the stabilizing measurement-free quantum controller used in fully quantum closed-loop system. The task is to minimize an infinite-horizon mean square performance index. This problem is called Coherent Quantum Linear Quadratic Gaussian (CQLQG) [510]. Another optimization problem is the decomposing of unitary matrices obtained by a quantum algorithm to so-called two level matrices [511]. Some recent developments helps reduce the complexity of the analysis when quantum systems have been described as networks of quantum nodes. This opens an area of optimizational tasks like optimizing the convergence rate of the continuous time quantum consensus algorithm [512], [513] and optimizing the convergence rate of the gossip algorithm for quantum networks [514], optimal configuration of the LQR controller [515], improvement of quantum control fidelity for noisy system [516]. Constraints of the hardware are one of the main difficulties faced in the process of running quantum algorithms. The quantum circuits must be compiled for the specific hardware, to make sure that the algorithm has been run properly. The usage of more flexible quantum circuits makes it challenging to find the optimal compilation. In [517] the Quantum Approximate Optimization Algorithm is in focus for finding the optimal circuit design.

## XI. Conclusion.

In this paper an extensive analysis of the quantum information technology and the quantum computing was presented. The classification of the different research areas where the quantum technology is connected with other fields gives an idea of what should be expected within the near future. As it seems most of the research is focused in the field of theoretical computer science and the computational complexity. Still there are too few applications of the quantum computing which could make a significant change to a specific area. Quantum hardware development would definitely lead to the broader research in algorithms and software. We hope the content provides a useful overview for technically informed readers. We have tried to minimize the technical details which could be distracting or off-putting for a broader audience.

## XII. Acknowledgment.

We acknowledge the use of "Cornel University Library" and its search engine, which can be found at the following web site: https://arxiv.org . All the views expressed are those of the authors and do not reflect the official position or policy of Cornel University Library.

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