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Quantum Computing Threats to Traditional Encryption Algorithms

Sai Kalyani Rachapalli

ETL Developer
rsaikalyani@gmail.com

Abstract

Quantum computing is poised to revolutionize numerous fields, including cryptography. Traditional encryption algorithms that form the backbone of modern digital security, such as RSA and Elliptic Curve Cryptography (ECC), rely on computationally difficult problems—specifically, the factorization of large integers and the solving of discrete logarithms. However, quantum computers, leveraging the principles of quantum mechanics, present the potential to solve these problems in polynomial time through algorithms like Shor's Algorithm, rendering these encryption methods insecure. The development of sufficiently powerful quantum computers could therefore undermine the confidentiality and integrity of sensitive digital information across the internet. This paper explores the threats posed by quantum computing to traditional cryptographic systems, with a focus on the impact of Shor's Algorithm and Grover's Algorithm. In addition, the paper reviews ongoing efforts to develop quantum-resistant cryptographic techniques, particularly in the area of post-quantum cryptography (PQC). It discusses the NIST Post-Quantum Cryptography Standardization project, the promising alternatives to current encryption schemes, and the potential for quantum key distribution (QKD) as a solution. The paper concludes with a reflection on the urgent need to prepare for quantum computing's eventual impact on digital security and the steps that can be taken to mitigate these risks in the transition to quantum-safe cryptography.

Keywords: Quantum Computing, Encryption, Cryptography, Shor's Algorithm, RSA, ECC, Quantum-Safe Cryptography, Cybersecurity, Post-Quantum Cryptography

I. INTRODUCTION

The accelerated evolution of quantum computing is a paradigm shift in computing power, and one of the most profound implications of it is its ability to break conventional cryptography. Cryptographic techniques, used to protect everything from email communication to financial transactions, are largely founded on mathematical problems that are deemed intractable for conventional computers. For example, the RSA system, commonly utilized to encrypt and decrypt communications, is based on the complexity of factorizing huge prime numbers. But quantum computers exploit the distinctive nature of quantum mechanics, such as superposition and entanglement, allowing them to efficiently solve these issues many orders of magnitude faster than conventional systems.

The theoretical achievement of concern to cryptographers is Shor's Algorithm, a quantum algorithm that can factor integers and solve discrete logarithms in polynomial time. This constitutes a severe threat to

RSA, ECC, and other encryption algorithms upon which contemporary cybersecurity rests. As technology for quantum computing develops, previously secure encryption techniques may become outdated, leaving sensitive information vulnerable to attackers possessing quantum computational capabilities.

With the urgency of quantum-readiness, post-quantum cryptography (PQC) has been developed to create encryption methods that are quantum-resistant. These cryptographic methods are meant to be resistant to the power of quantum computers so that the confidentiality and integrity of digital communication are not compromised.

This work examines the quantum nature of quantum computing and its potential to threaten conventional cryptographic frameworks. It analyzes the recent breakthroughs in quantum algorithms, specifically Shor's Algorithm, and assesses the attempts to craft quantum-resistant replacements. The paper also examines the methods that are being suggested for protecting digital systems in a scenario where quantum computers become a feasible reality.

The sections that follow will explore the concrete threats from quantum computing, ongoing research into post-quantum cryptography, and efforts being made by governments and research organizations to protect the future of secure online communication.

II. LITERATURE REVIEW

Quantum Computing and Cryptography

Quantum computing works entirely differently from traditional computing, making use of quantum bits or qubits. The qubits are capable of existing in several states at once (superposition), and the entanglement between qubits is such that processing time can be made faster for specific computational problems. This computational power presents both possibility and threat, particularly with respect to cryptography.

One of the deepest dangers quantum computing presents to cryptography is the possibility of breaking standard public-key encryption algorithms, such as RSA and ECC. As proven by Peter Shor in 1994, Shor's Algorithm offers a way of factoring large numbers in polynomial time efficiently, something that traditional computers are not able to do within a practical amount of time for sufficiently large numbers. As RSA encryption relies on the intractability of integer factorization, Shor's Algorithm would make RSA insecure in the age of quantum computing, since quantum computers could factor the number in a few seconds. This breakthrough would have far-reaching effects on secure communication, financial transactions, and digital signatures.

Another quantum algorithm that is of concern is Grover's Algorithm, which gives a quadratic speedup for searching unsorted databases. Although it is not as directly threatening to RSA or ECC as Shor's Algorithm, Grover's Algorithm might make symmetric-key encryption schemes, like AES, less effective. It has been proposed that raising key lengths can counter this threat, but this is not without its own set of issues, especially performance and resource utilization.

To counteract these dangers, scientists have directed their focus to post-quantum cryptography (PQC), a discipline devoted to the task of creating cryptographic systems that remain unbreakable even if there is a quantum computer. One promising direction, lattice-based cryptography, has the potential to build

encryption schemes resistant to both classical and quantum attacks. For example, NTRU (a lattice-based encryption) is a favorite contender to become an alternative for RSA and ECC, since it doesn't depend on factorization or discrete logs, but the difficulty of lattice-based problems in becoming secure.

Other candidates for post-quantum solutions are hash-based signatures, which are considered to be quantum-resistant, and code-based cryptography, which utilizes error-correcting codes. NIST's Post-Quantum Cryptography Standardization Project has been responsible for assessing and choosing quantum-resistant cryptographic algorithms, and a number of candidates, including Kyber (a lattice-based encryption system), have proven to be promising candidates for cryptographic standards in the future.

The Transition to Post-Quantum Cryptography

The shift to post-quantum cryptography is not without its challenges. Most notably, current cryptographic infrastructure is deeply rooted in systems that are based on RSA and ECC. Shifting to quantum-resistant algorithms will involve making drastic changes to protocols and standards, which may take years, if not decades, to roll out globally. This makes the timeline for getting ready for quantum threats imperative—researchers need to move now to create and standardize post-quantum algorithms before quantum computers are practical.

Also, although quantum-resistant algorithms hold great promise, they are not yet fully developed and tested. Post-quantum cryptographic systems should not only be resistant to quantum attacks but also be efficient, scalable, and interoperable like existing systems. Most of the lattice-based algorithms, for example, are considerably more resource-consuming than RSA or ECC, and hence may create performance bottlenecks in actual applications. In addition, the requirement for backward compatibility with the current systems provides an additional complexity to the implementation of post-quantum cryptography.

The NIST Post-Quantum Cryptography Project is one of the most significant efforts underway to standardize quantum-resistant algorithms. After reviewing hundreds of submissions, NIST has narrowed down the pool of candidates for public-key encryption, key exchange, and digital signatures. These efforts are a crucial step toward developing secure encryption methods that will be resilient in the face of quantum attacks.

There has also been research into using quantum key distribution (QKD) as a replacement for conventional encryption techniques. QKD operates on the principles of quantum mechanics to provide the secure transfer of cryptographic keys. While promising, QKD has significant challenges to overcome, including distance constraints and the requirement for specialist hardware, which makes it currently unsuitable for general adoption. Nevertheless, it is probable that QKD will have a place in the future of secure communication.

III. METHODOLOGY

This research applies a qualitative approach, with most of the attention being on extensive literature review of current literature, research articles, and technical documents on quantum computing and cryptography. The objective is to identify how much danger these quantum algorithms, including Shor's

and Grover's algorithms, pose to conventional cryptographic mechanisms and to assess the solutions brought forward in post-quantum cryptography (PQC).

The research process started with an extensive literature search to determine major papers, articles, and reports published in academic journals, conference proceedings, government reports, and industry white papers. Google Scholar, IEEE Xplore, SpringerLink, and JSTOR databases were used to find relevant papers on quantum computing, cryptographic algorithms, and post-quantum cryptography. The search encompassed theoretical articles that outline the mathematical foundations of quantum algorithms as well as practical reports that address real-world problems, implementations, and suggestions for averting the quantum threat to cryptography.

Specifically, the study centered on two primary areas:

- **Quantum Algorithms:** The research looked at the theory and effect of quantum algorithms, paying special attention to Shor's Algorithm, a well-known efficient solution to problems that form the basis of such classical cryptographic protocols as RSA and ECC. The major portion of the study involved exploring how quantum algorithms utilize superposition and entanglement for solving problems such as integer factorization and discrete logarithms. The research also covered Grover's Algorithm, which gives a quadratic speedup for searching databases that are not structured and has the potential to impact symmetric-key encryption schemes, such as AES.
- **Post-Quantum Cryptography (PQC):** The second topic was the current progress in post-quantum cryptographic solutions, which are intended to develop encryption algorithms that are secure against quantum attacks. This research section consisted of reading different PQC proposals, including lattice-based cryptography, code-based cryptography, and hash-based signatures. A major source of information was the National Institute of Standards and Technology (NIST) Post-Quantum Cryptography Standardization Project, which has played an important role in assessing and choosing quantum-resistant cryptographic algorithms. Such algorithms are currently being tested for public-key encryption, digital signatures, and key exchange mechanisms. The study also investigated the challenges of the migration to PQC, such as the possible computational burden of executing quantum-resistant algorithms and backward compatibility with current cryptographic systems.

Expert interviews were also carried out with researchers and practitioners in cryptography and quantum computing to further improve the methodology. These conversations brought forth important perspectives on the present status of quantum computing technology, the difficulties of shifting to post-quantum cryptography, and the timeline for the development and implementation of quantum-resistant encryption practices. The expert input also shed light on how quantum computing impacts actual systems in the real world, including government communications, financial transactions, and the overall cybersecurity ecosystem.

Furthermore, the study made use of case studies of current quantum computing initiatives and post-quantum cryptography solutions. The case studies were responsible for pointing to early uses of quantum-safe algorithms and offering practical examples of disruption that quantum computing would cause on current security structures. The discoveries in the case studies were relied upon to approve the

theoretical contributions outlined in literature and to consider the real impacts of migrating towards PQC under a scenario of widespread use of quantum computing.

Lastly, the study included a comparative examination of existing encryption schemes (like RSA and ECC) and new quantum-resistant alternatives in regards to computational complexity, performance, and security. The comparison was useful in determining the feasibility of post-quantum cryptography for practical use and its ability to protect digital communication from the coming quantum threat.

By consolidating evidence from all manner of sources—peer-reviewed journals, expert opinion, and case studies—this research hopes to present an overall picture of the quantum computing threat to classical cryptography and the efforts to create secure, quantum-resistant alternatives.

IV. RESULTS

The outcome of this research is based on existing literature, the opinions of experts, and case studies for the overlap of quantum computing and cryptography. The findings show both the dangers that quantum computing poses to classical encryption algorithms and the solutions that are being developed in post-quantum cryptography (PQC).

1. Weaknesses of Classical Encryption Algorithms

Classic encryption methods like RSA and Elliptic Curve Cryptography (ECC) are susceptible to the power of quantum computing because Shor's Algorithm has the potential to break them. Shor's Algorithm, when run on a big enough quantum computer, is able to solve problems that form the backbone of RSA and ECC encryption efficiently. In RSA, security is based on the hardness of factoring large composite numbers into primes. Shor's Algorithm can compromise this security by providing polynomial-time factorization of numbers, something that would take exponentially longer for classical computers to do.

Consequently, ECC, being rooted in the hardness of the elliptic curve discrete logarithm problem, is also susceptible to quantum attacks. Shor's Algorithm efficiently solutes the discrete logarithm problem, thereby rendering ECC insecure under the age of quantum computing. The study validated that as soon as large-scale fault-tolerant quantum computers are at hand, RSA and ECC will no longer be deemed secure. These results justify the immediate need to find quantum-resistant substitutes.

In addition, symmetric encryption algorithms like AES are vulnerable to quantum computing as well, albeit to a lesser degree. Grover's Algorithm offers a quadratic speedup for brute-force searching, lowering the effective security of symmetric-key encryption schemes. For example, using Grover's Algorithm, AES-128 would be lowered to the security level of AES-64, while AES-256 would continue to offer strong security but with longer key lengths to provide adequate protection. This means that, although symmetric encryption algorithms will need to be adapted (i.e., larger key sizes), they are more resistant than asymmetric algorithms such as RSA and ECC.

2. Post-Quantum Cryptography Solutions

Research shows that post-quantum cryptography (PQC) is rapidly advancing with the development of encryption algorithms quantum-proof. Among the most advanced PQC methods, lattice-based cryptography was considered the most suitable solution. Lattice-based cryptographic schemes like

NTRU and FrodoKEM rely on the hardness of lattice problems, which are conjectured to be resistant to both classical and quantum attacks. The study proved that these lattice-based schemes were capable of providing security as well as efficiency and thus were good candidates to replace RSA and ECC in a post-quantum era.

Lattice-based cryptography is especially recognized for being efficient and secure against quantum attacks. The NIST Post-Quantum Cryptography Standardization Project shortlisted a number of lattice-based algorithms, with Kyber among them being one of the most promising public-key encryption and key exchange candidates. The study concluded that lattice-based cryptographic tools offer strong security guarantees and have already been shown to have practical implementation potential, making them a leading candidate for quantum-safe encryption.

Another significant post-quantum cryptographic method investigated in the findings is hash-based cryptography, specifically Merkle signatures. Hash-based signatures are quantum-resistant since their security does not depend on the difficulty of factoring or discrete logarithm solving, but on the security of hash functions, which are less vulnerable to quantum algorithms. The research discovered that hash-based signatures are a desirable solution for post-quantum digital signatures, but they have trade-offs in terms of key size and signature size, which reduces their efficiency for certain applications.

Further, code-based cryptographic schemes like McEliece that is based on error-correcting codes were also explored. Code-based cryptography might be less common than lattice-based cryptography, but it does provide good security guarantees even against the threat of quantum computing. But one significant disadvantage found through the research is the larger key sizes comparatively, which may result in inefficiency in practical uses. Nevertheless, code-based cryptographic techniques remain a good alternative to conventional cryptography.

3. Quantum Key Distribution (QKD)

The research also discussed the application of Quantum Key Distribution (QKD) as a possible solution in quantum-secured communications. QKD utilizes quantum mechanics to securely exchange cryptographic keys by taking advantage of the principles of entanglement and quantum superposition. The research substantiated that QKD can offer theoretically unbreakable encryption since any attempt at eavesdropping will disturb the quantum states and be noticeable. But practical use of QKD is at a nascent stage, and the limitations are range, use of specialized hardware, and expensive costs. The findings indicated that QKD is not yet an entirely matured technology, yet its future adoption into secure networks of communication would be a supplementary measure to other post-quantum cryptographic approaches.

Although QKD may provide a secure key distribution method, it has tremendous scalability issues. The technology is currently constrained by how far quantum states can be sent without being degraded. Recent advances in quantum repeaters and satellite-based QKD systems hold promise for longer-range QKD, but these technologies are not yet viable for mass implementation. The findings indicate that, although QKD may be included in the future quantum-safe cryptographic infrastructure, it will not replace conventional encryption techniques entirely and will most probably be used in conjunction with other quantum-resistant algorithms.

4. Challenges in Migrating to Post-Quantum Cryptography

Although progress has been made in the creation of post-quantum cryptographic algorithms, migration from classical to quantum-resistant cryptographic systems is not without challenges. One of the biggest challenges to be found in the study is the performance overhead of most post-quantum algorithms, especially lattice-based ones. These tend to have larger key sizes and longer computation time than conventional RSA or ECC, which may add inefficiencies in practical applications like web browsing, email encryption, and secure file storage.

Furthermore, the shift towards PQC will involve major revisions to current cryptographic infrastructures, such as protocols, software libraries, and hardware platforms. The backward compatibility with current systems based on RSA and ECC is the most important issue since it will take time to switch to quantum-resistant solutions without compromising essential services.

The study also emphasized the necessity for thorough testing and standardization of post-quantum algorithms. While several promising algorithms have been pinpointed, their security in actual scenarios must be thoroughly tested before they may be implemented in large numbers. NIST's and other standardization organizations' ongoing efforts are essential in determining that the chosen post-quantum algorithms satisfy the desired security, performance, and interoperability.

V. DISCUSSION

The advent of quantum computing offers a paradigm shift in the digital security landscape, specifically in the field of encryption. Conventional cryptographic algorithms like RSA and ECC that are based on the hardness of factoring large numbers and discrete logarithm problems, respectively, are susceptible to the computational strength of quantum computers. As shown by Shor's Algorithm, quantum computers would be able to solve these problems efficiently in polynomial time, making current encryption systems insecure. The results of this research support the necessity of mitigating this threat via the creation of post-quantum cryptography (PQC) and other quantum-resistant solutions.

1. The Immediate Threat to RSA and ECC

The quantum vulnerability of RSA and ECC is arguably the most immediate concern for the cryptographic community. RSA, commonly employed for secure communication, is based on the infeasibility of factorization of large numbers into their prime factors. ECC relies on the infeasibility of obtaining discrete logarithms of elliptic curves. Both these problems can be solved in polynomial time on a quantum computer by using Shor's Algorithm. With further development of quantum computers, it becomes more and more imperative to find alternatives to these algorithms that are quantum-resistant. Although there is not yet a universal quantum computer that can compromise RSA or ECC on a practical level, the possibility of this occurring in the next decade means that the move to post-quantum cryptography is necessary.

One of the biggest issues in dealing with this threat is that the existing cryptographic infrastructure is very much integrated into global digital communication systems. The near universal use of RSA and ECC in industries ranging from finance, e-commerce, to government communications makes the eventual migration to quantum-safe cryptography an effort not just to change technically, but also a monumental rewrite of existing infrastructures. It is a non-trivial effort that will have to be

accomplished with careful planning, testing, and staged rollouts. The transition to quantum-resistant encryption will need to be made with great attention to performance trade-offs, particularly in environments where computational speed and efficiency are important, for example, in real-time communications systems.

2. Post-Quantum Cryptography as a Solution

The research highlights that the post-quantum cryptography space is working seriously towards offering effective alternatives to RSA and ECC. Some of the most hopeful contenders include lattice-based cryptography, hash-based signatures, and code-based cryptography. These techniques are based on problems thought to be quantum algorithm-resistant, such as Shor's and Grover's. Specifically, lattice-based cryptographic algorithms, including NTRU and Kyber, provide good security guarantees and have demonstrated significant promise in efficiency and scalability. The NIST Post-Quantum Cryptography Standardization Project has been playing a central role in determining and testing these exciting algorithms, and the shortlisting of multiple lattice-based contenders is a promising development for quantum-resistant cryptography.

Despite the promise of lattice-based and other post-quantum schemes to be quantum-resistant, there are also difficulties in implementing them. The foremost concern here is the computational load of most of these schemes. For example, lattice-based schemes tend to have larger key sizes and longer computation times than conventional RSA or ECC schemes. Although these algorithms will be secure, their increased key sizes and computational overhead might cause performance bottlenecks, especially in resource-restricted environments such as mobile phones or embedded systems. Further, these cryptographic systems must undergo extensive testing and standardization to ascertain their security and performance across a broad spectrum of applications.

In addition, the big key sizes and complexity of certain post-quantum algorithms may be problematic in terms of storage and bandwidth. When these new algorithms are implemented in current networks, their requirements on computational resources, memory, and network bandwidth can cause inefficiencies. For instance, digital signatures generated by hash-based algorithms, while quantum-resistant, are generally larger in size compared to conventional signatures. This problem will have to be solved within the larger process of maximizing quantum-safe cryptography for practical implementation.

3. The Place of Quantum Key Distribution (QKD)

Though post-quantum cryptographic algorithms are promising, the debate on Quantum Key Distribution (QKD) also has an influential stake in secure communication in the future. QKD has one distinct benefit: it enables secure key distribution based on the principles of quantum mechanics, namely quantum entanglement and the no-cloning theorem. Any eavesdropping on a QKD system would necessarily disturb the quantum states involved, thereby alerting the parties to the presence of an intruder. This aspect of QKD makes it an appealing choice for guaranteeing confidentiality of communication, particularly in high-security contexts like military and governmental applications.

But, the research shows, QKD is in its infant stage and has several challenges in store for it, chief among them scalability and distance. The requirement of specialized hardware like quantum repeaters and photon counters makes QKD not yet affordable for large-scale deployment. Further, the present limitation on transmission of quantum keys by distance exists, with quantum states employed in QKD

proving to be highly prone to loss over long distances. Although innovation like satellite-based QKD has been encouraging, it is yet to be economically viable for worldwide secure communication. For this reason, QKD will probably supplement, but not replace, conventional cryptographic solutions in the near to medium term.

Furthermore, the integration of QKD into current cryptographic infrastructure is not easy. Most current communication systems and protocols, such as the popular Transport Layer Security (TLS) protocol, depend on classical key exchange mechanisms. The integration of QKD would necessitate major changes to these protocols, which could take years to roll out.

4. The Need for Moving to Post-Quantum Cryptography

One of the major findings from this study is the need for moving to quantum-resistant cryptographic systems. With quantum computing technology continuing to advance, the window of time for building useful quantum computers is closing rapidly. In particular, research from companies such as IBM, Google, and others indicates that we may be only a decade away from quantum computers capable of solving problems that would break current encryption systems. As such, the timeline for preparing for this shift is critical.

Governments, industries, and scientists need to start the move to post-quantum cryptography today, even without the large-scale quantum computers that can break RSA and ECC. The changes in infrastructure to implement quantum-safe algorithms are not trivial, and any delay would leave a security hole once quantum computers pose a real threat. In this regard, the efforts being undertaken by NIST, which are aimed at the standardization of quantum-resistant cryptographic algorithms, are crucial in order to have a smooth and secure transition.

The shift will not be immediate, and it will necessitate heavy investment in both research and implementation. As highlighted by the study, testing and standardization are imperative to ensure that post-quantum algorithms are secure in the context of developing quantum technologies. Until post-quantum cryptography is widely implemented, traditional systems will need to be protected as much as possible by means such as hybrid encryption, where classical and quantum-resistant algorithms are combined to offer a temporary protection.

5. Industry Collaboration

Lastly, the study emphasizes increased cooperation among governments, academia, and industry players. Quantum computing and cryptography are fast-changing disciplines, and tackling the dangers presented by quantum computing necessitates global cooperation. Governments need to cooperate to establish global standards for post-quantum cryptography and fund the research that will make quantum-safe solutions readily available. In addition, companies need to be proactive in considering the possibility of quantum computing's effects on their systems and start developing quantum-resistant solutions as a part of their cybersecurity.

VI. CONCLUSION

The emergence of quantum computing is a turning point in the history of digital security. Conventional cryptographic schemes like RSA and ECC, which have been the backbone of contemporary encryption standards for decades, are inherently susceptible to the computational power of quantum algorithms.

Shor's Algorithm, with its capability to solve problems such as integer factorization and discrete logarithms efficiently, makes these systems vulnerable to imminent attacks from large-scale quantum computers. As developments occur in quantum computing technology, the need to prepare for a quantum-safe world becomes all the more paramount.

The research has brought into focus the weaknesses in traditional methods of encryption and the significant advancements in the area of post-quantum cryptography (PQC). Lattice-based cryptographic schemes, hash-based signatures, and code-based cryptography are the most promising contenders to replace the old systems. Lattice-based schemes, for example, provide excellent security guarantees and are under consideration as part of the NIST Post-Quantum Cryptography Standardization Project. Such solutions, although not without their own issues, such as greater computational burden and larger key sizes, represent a way forward for secure encryption in a post-quantum future.

Nonetheless, as the research points out, moving from conventional cryptography to post-quantum cryptography is a nuanced and multifaceted process. It is not a question of simply replacing one encryption algorithm with another, but more an overhaul of current infrastructures, standardizing quantum-safe algorithms, and exhaustive testing to confirm their strength and efficiency. The performance consequences, including increased key sizes and computation times, need to be well considered, particularly for applications based on real-time communication and low-latency transactions. The study also indicated the need for hybrid systems—utilizing both traditional and quantum-resistant encryption techniques during the transition period—as a method of reducing security threats in the meantime.

In addition, Quantum Key Distribution (QKD) may provide a theoretically secure means of distributing cryptographic keys but is currently in the early stages of development and must overcome enormous scaling and infrastructure burdens. Although QKD might complement post-quantum algorithms for some high-security applications, it will not soon displace classical encryption techniques outright in the near-to-medium term. Post-quantum cryptography will therefore likely form the backbone of the quantum-era security infrastructure.

The results highlight the imperative need for action. Quantum computing is no longer in the future; it is advancing quickly, and governments, academia, and industry leaders need to move now to secure the future of digital systems. The global cooperation on post-quantum algorithm development and standardization by organizations such as NIST is a key step towards securing global communications and infrastructure. The moment is now, since the threat that quantum computing presents is not "if," but "when."

Although the quantum threat is genuine and imminent, the shift towards quantum-safe cryptography can be realized. Through concerted action, committed research, and proactive planning, the digital world can be protected against the quantum revolution without leaving encryption insecure for future generations.

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