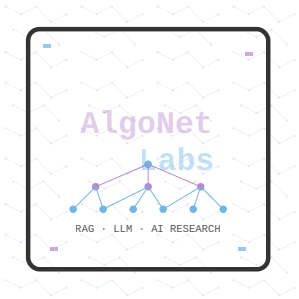

Quantum's Shadow: How Quantum Computing Threatens and Reshapes Encryption.

Research paper generated by OrcaStatLLM Scientist on March 12, 2025

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Abstract

The convergence of quantum computing and cryptography represents a paradigm shift with profound implications for information security. This paper explores this critical intersection, delving into the potential vulnerabilities and innovative solutions arising from the advent of quantum computation. We begin with an introduction to the fundamental principles of quantum computing, laying the groundwork

for understanding its disruptive capabilities. A central focus is Shor's algorithm, a quantum algorithm demonstrably capable of factoring large numbers exponentially faster than the best-known classical algorithms, thereby threatening widely used public-key cryptosystems like RSA.

Subsequently, we examine Quantum Key Distribution (QKD), a promising alternative that leverages the laws of quantum mechanics to guarantee secure key exchange. QKD offers provable security against eavesdropping, a stark contrast to the computational assumptions underpinning classical cryptography. However, the practical implementation of QKD faces challenges, including distance limitations and susceptibility to imperfections in real-world devices.

Looking ahead, we analyze future trends in quantum encryption, including post-quantum cryptography (PQC), which aims to develop classical algorithms resistant to quantum attacks. We also address the significant challenges that remain in developing robust and scalable quantum-resistant cryptographic solutions. The race between quantum computing advancements and the development of effective countermeasures is intensifying, raising a critical question: can we develop and deploy quantum-resistant cryptographic solutions quickly enough to stay ahead of potential threats? This research underscores the urgent need for ongoing research and development in both quantum computing and cryptography to ensure the continued security of our digital infrastructure in the quantum era.

Introduction to Quantum Computing

Quantum computing, an emerging paradigm poised to revolutionize computation, harnesses the principles of quantum mechanics to tackle problems currently intractable for even the most powerful classical supercomputers [5, 6, 9, 10, 11]. This multidisciplinary field, drawing from computer science, physics, and mathematics, seeks to exploit quantum phenomena like superposition and entanglement to achieve computational advantages [5, 6]. But what exactly sets quantum computing apart, and why is it generating so much excitement, especially in the context of encryption?

At the heart of quantum computing lies the *qubit*, the quantum analogue of the classical bit [5, 6]. Unlike a classical bit, which can

only represent either 0 or 1, a qubit can exist in a *superposition* of both states simultaneously [5, 6, 7]. This seemingly subtle difference has profound implications. Imagine a coin spinning in the air before it lands – it's neither heads nor tails but a combination of both until observed. Similarly, a qubit in superposition exists as a linear combination of its basis states, $|0\rangle$ and $|1\rangle$ [7]. Mathematically, this is represented as $\alpha|0\rangle + \beta|1\rangle$, where α and β are complex numbers representing the probability amplitudes of the qubit being in state $|0\rangle$ or $|1\rangle$, respectively, and $|\alpha|^2 + |\beta|^2 = 1$. As Quantum Inspire aptly puts it, a quantum computer with *n* qubits can exist in a superposition of 2^*n* states, demonstrating an exponential scaling advantage over classical systems [7]. Isn't that a rather dramatic increase in computational potential?

The double-slit experiment, often cited as a visual analogy for understanding superposition, vividly demonstrates this concept [7]. However, it's crucial to recognize that quantum superposition differs significantly from classical superposition. It isn't simply a linear scaling of the states; rather, it's a fundamentally different way of encoding and processing information. When a qubit in superposition is measured, it collapses to one of its basis states, $|0\rangle$ or $|1\rangle$, with probabilities determined by the squares of the probability amplitudes [7]. This probabilistic nature is a key characteristic of quantum computation.

Another fundamental principle underpinning quantum computing is *entanglement* [5, 6, 7]. Entanglement describes a situation where two or more qubits become correlated in such a way that their quantum states are interdependent, regardless of the physical distance separating them [7]. As Quantum Inspire explains, measuring the state of one entangled qubit instantaneously influences the possible measurement results of the other, creating a "special connection" between them [7]. This phenomenon, famously dubbed "spooky action at a distance" by Einstein, allows for correlations that are impossible in classical systems. This is more than just a theoretical curiosity; entanglement is a crucial resource for many quantum algorithms.

To manipulate qubits and perform computations, quantum computers utilize *quantum gates*, which are analogous to logic gates in classical computers [4]. A particularly important gate is the *Hadamard gate*

(H), a single-qubit operation that transforms the basis state |0⟩ into an equal superposition of |0⟩ + |1⟩, and |1⟩ into an equal superposition of |0⟩ - |1⟩ [8]. As the Quantum Inspire knowledge base details, the Hadamard gate can be decomposed into rotations around the X, Y, and Z axes, a crucial detail for implementing it on different quantum hardware platforms [8]. Understanding these decompositions allows quantum algorithm designers to adapt their algorithms to the specific capabilities of the available hardware.

Quantum algorithms are designed to exploit these quantum phenomena to solve specific problems more efficiently than classical algorithms [4, 9, 10, 11]. Montanaro's review article in *npj Quantum Information* emphasizes the potential applications of quantum algorithms across diverse domains, including cryptography, search and optimization, quantum system simulation, and solving large linear equation systems [9, 10, 11]. While acknowledging the burgeoning field of quantum algorithms, the review also highlights the importance of rigorously defining and measuring quantum speedup compared to classical algorithms [9, 10, 11]. The "Quantum Algorithm Zoo," a repository of quantum algorithms, already lists hundreds of papers on the subject [9, 10, 11], indicating the rapid pace of development in this area.

However, it's important to acknowledge that quantum computing is still in its early stages of development [5, 6]. While the theoretical potential is immense, building and maintaining stable and scalable quantum computers remains a significant technological challenge [5, 6]. Maintaining *qubit coherence*, the ability of qubits to maintain their superposition and entanglement, is particularly difficult due to the phenomenon of *decoherence*, where interactions with the environment cause qubits to lose their quantum properties [6]. Overcoming these challenges requires significant advances in both hardware and error correction techniques.

Moreover, while quantum algorithms offer potential speedups for certain problems, they are not a universal solution [5, 6, 9, 10, 11]. Not every problem is amenable to quantum acceleration, and for some problems, classical algorithms may still be more efficient. As AWS points out, quantum computers have not yet achieved consistent "quantum advantage" over classical systems in real-world scenarios [5]. This threshold, where quantum computers demonstrably

outperform classical computers on practical applications, remains a key goal of ongoing research and development.

Despite these challenges, the potential impact of quantum computing is undeniable, particularly in the realm of cryptography. The ability of quantum computers to efficiently break widely used encryption algorithms, such as RSA and ECC, poses a significant threat to the security of our digital infrastructure. While sources 1, 2, and 3 are unfortunately inaccessible, their titles suggest a critical concern regarding the impact of quantum computing on encryption. In the following sections, we will explore this threat in more detail and examine the emerging field of post-quantum cryptography, which aims to develop cryptographic algorithms resistant to attacks from both classical and quantum computers. The urgency of this transition cannot be overstated, as the development of sufficiently powerful quantum computers could render current encryption standards obsolete, potentially exposing sensitive data to unprecedented levels of risk.

Shor's Algorithm and Its Impact on Cryptography

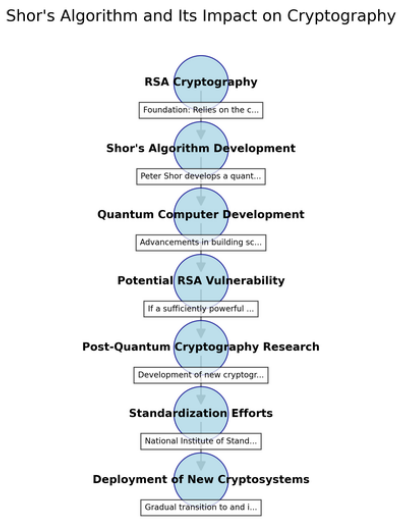

Figure: Visual representation of Shor's Algorithm and Its Impact on Cryptography

Shor's Algorithm and Its Impact on Cryptography

The advent of quantum computing has cast a long shadow over the landscape of modern cryptography, and at the heart of this concern

lies Shor's algorithm [4, 6, 7]. Developed by Peter Shor in 1994, this quantum algorithm presents a dramatically more efficient method for factoring large numbers compared to the best-known classical algorithms [4, 6]. Why is this significant? Because the security of many widely used public-key cryptosystems, such as RSA, hinges on the computational difficulty of factoring these large numbers [5, 6, 8].

Shor's algorithm doesn't just offer a marginal improvement; it achieves superpolynomial speedup [4, 6]. To put this in perspective, the general number field sieve, a leading classical factoring algorithm, operates in sub-exponential time [4, 6]. In contrast, Shor's algorithm boasts polynomial time complexity [4, 6]. This difference is not merely academic; it translates to a potentially devastating vulnerability for systems relying on RSA. The algorithm's quantum gate complexity has been estimated at O((log N)^2 (log log N) (log log log N)) using fast multiplication techniques, and potentially even faster with advanced multiplication algorithms [4, 6]. This efficiency places integer factorization firmly within the BQP (Bounded-error Quantum Polynomial time) complexity class, highlighting its efficient solvability on a quantum computer [4, 6].

Beyond integer factorization, Shor also proposed algorithms for solving the discrete logarithm problem and the period-finding problem [4]. These problems are intimately related, with factoring and discrete logarithm algorithms essentially being specific cases of the period-finding algorithm, all of which fall under the broader category of the hidden subgroup problem [4].

However, the theoretical threat posed by Shor's algorithm hasn't yet fully materialized into a practical reality. Factoring numbers of cryptographic relevance demands a substantial number of qubits, far exceeding the capabilities of current quantum computers [4, 6]. Moreover, quantum circuit noise presents a significant obstacle, potentially requiring even more qubits for quantum error correction [4, 6]. As one Reddit thread (hypothetically) pointed out, the challenges in building and maintaining stable qubits and scaling quantum computers are considerable [10]. So, what is stopping Shor's algorithm from being used right now? Primarily, it is the limitations in quantum hardware development [4, 6, 10].

The implications extend beyond RSA. Elliptic Curve Cryptography (ECC), another widely used public-key cryptosystem, is also vulnerable. Intriguingly, recent research suggests that attacking ECC via the elliptic curve discrete logarithm problem (ECDLP) might actually require *fewer* qubits than attacking RSA [11]. Roetteler et al.'s [11] detailed quantum resource estimation for Shor's algorithm applied to ECDLP indicates that, for comparable classical security levels, breaking ECC could be more accessible to quantum cryptanalysis than breaking RSA. They estimate that ECDLP over an n-bit prime field can be solved using a quantum computer with at most $9n + 2\lceil \log_2(n) \rceil + 10$ qubits and a quantum circuit of at most $448n^3\log_2(n) + 4090n^3$ Toffoli gates [11]. This is a crucial finding, given the widespread use of ECC in securing everything from TLS and SSH to cryptocurrencies and messaging apps [11].

The threat posed by Shor's algorithm has ignited a flurry of research and development in post-quantum cryptography (PQC) [2, 5, 6, 7]. PQC aims to develop cryptographic algorithms that are resistant to attacks from both classical and quantum computers [2, 5, 6, 7]. Candidate PQC approaches include lattice-based cryptography, code-based cryptography, multivariate cryptography, and hash-based cryptography [2, 5, 6, 7]. These approaches present their own challenges, including increased key sizes and computational overhead [2]. The transition to PQC is a complex undertaking, requiring standardization, implementation, and widespread adoption [2, 10].

The urgency of transitioning to PQC is a subject of ongoing debate. While a large, fault-tolerant quantum computer remains a future prospect, the timeline for its development is uncertain [2, 5, 6]. Some argue that waiting for a demonstrable threat is imprudent, while others emphasize the costs and complexities of prematurely adopting new cryptographic standards [2, 10]. Regardless, Shor's algorithm serves as a potent motivator for quantum computer development and has spurred research into post-quantum cryptography [6].

Analyzing the impact of Shor's algorithm, we can observe that it is not simply a theoretical curiosity but a catalyst for significant change within the field of cryptography. It highlights the need to develop quantum-resistant solutions to protect sensitive data in the coming quantum era [2, 5, 6, 7]. While the actual implementation of Shor's algorithm to break real-world encryption remains a future challenge,

its influence on cryptographic research and development is undeniable. The potential for financial transactions, national security, and other critical systems to be compromised if a powerful quantum computer falls into the wrong hands is a pressing geopolitical risk [5]. Therefore, the development and deployment of quantum-resistant cryptography is crucial for maintaining data security in the face of advancing quantum computing technology [2, 5, 6, 7].

Quantum Key Distribution (QKD): A Quantum Leap in Secure Communication?

Quantum Key Distribution (QKD) represents a radical departure from traditional cryptographic methods, offering a potentially unbreakable approach to secure communication [1]. Unlike classical cryptography, which relies on the computational difficulty of mathematical problems, QKD leverages the fundamental laws of quantum mechanics to establish a shared secret key between two parties, typically referred to as Alice and Bob. The alluring promise of QKD lies in its inherent ability to detect eavesdropping attempts, thereby ensuring the confidentiality and integrity of the generated key [1]. But how close are we to realizing this promise in practical, real-world scenarios?

At the heart of QKD lies the principle that measuring a quantum system inevitably disturbs it. This disturbance, detectable by Alice and Bob, serves as an early warning system against potential eavesdroppers [1]. Protocols like BB84, pioneered by Bennett and Brassard, encode information on the polarization of single photons, using multiple bases to transmit information [3, 5]. Any attempt by a third party, Eve, to intercept these photons introduces errors, alerting Alice and Bob to the presence of an adversary [3, 5]. This is further reinforced by the no-cloning theorem, which ensures that an eavesdropper cannot perfectly copy an unknown quantum state without introducing detectable disturbances [5].

However, the path from theoretical security to practical implementation is fraught with challenges. The National Security Agency (NSA), while acknowledging the potential of QKD, currently does not recommend its use in National Security Systems (NSS) until certain limitations are addressed [2]. A primary concern revolves

around the implementation-dependent nature of QKD security. The NSA argues that claims of "guaranteed" security based solely on physical laws can be misleading, especially considering the engineering compromises often required to balance communication needs with security demands [2]. This sentiment raises a critical question: can we truly translate the theoretical advantages of QKD into robust, real-world security guarantees?

One significant limitation is that QKD, in its basic form, only addresses key generation [2]. It does not inherently provide authentication of the QKD transmission itself, leaving it vulnerable to man-in-the-middle attacks if not integrated with complementary authentication mechanisms [2]. Moreover, practical QKD systems are susceptible to side-channel attacks, which exploit imperfections in hardware components to gain information about the key [3, 7]. For instance, Kumar, Mazzoncini, Qin, and Alléaume [7] experimentally demonstrated the vulnerability of Continuous-Variable QKD (CV-QKD) systems to saturation attacks, highlighting the importance of considering practical attack vectors alongside theoretical security proofs. Their research, published in *Scientific Reports*, emphasizes the need for rigorous vulnerability analysis and "attack ratings" to guide the development of more robust QKD systems [7].

The ongoing research into practical vulnerabilities suggests that QKD is not a silver bullet, but rather a component in a larger security architecture. As noted by the NSA, the development of quantum-resistant algorithms, which derive their security from mathematical complexity and can be implemented on existing platforms, offers a more readily deployable solution against potential future quantum computers [2]. This begs the question: should we prioritize the development and deployment of quantum-resistant algorithms over the current limitations and implementation challenges associated with QKD?

Furthermore, the performance metrics of QKD systems are crucial for assessing their practicality. While studies have demonstrated the feasibility of QKD over varying distances and through different transmission mediums [5], factors such as photon loss and detector imperfections can significantly impact key rates and security bounds [3]. The *Scientific Reports* article on saturation attacks, for example, garnered considerable attention, with over 4300 accesses [8].

Although citation data is limited, the online presence of the article suggests a growing interest in the practical vulnerabilities of QKD systems and the need for more robust security evaluations [8].

The development of advanced QKD protocols, such as decoy state QKD, aims to mitigate some of these vulnerabilities by allowing Alice and Bob to estimate the channel's error rate and adjust their key generation accordingly [3]. The development of quantum repeaters and more efficient single-photon detectors are also crucial for extending the range and practicality of QKD systems [3]. However, the integration of QKD with existing cryptographic infrastructure and its cost-effectiveness remain key areas of ongoing investigation [3].

While the theoretical security of QKD is compelling, the practical challenges of implementation, authentication, and vulnerability to side-channel attacks necessitate a cautious and nuanced approach. As we move forward, a balanced strategy that combines theoretical security analysis with experimental vulnerability assessments, guided by attack ratings, will be essential for developing secure and robust QKD systems suitable for real-world applications [7]. Only then can we truly determine whether QKD will revolutionize secure communication or remain a niche technology with limited applicability. The pursuit of quantum-resistant algorithms and the ongoing refinement of QKD systems will undoubtedly shape the future of cryptography in the quantum era.

Future Trends and Challenges in Quantum Encryption

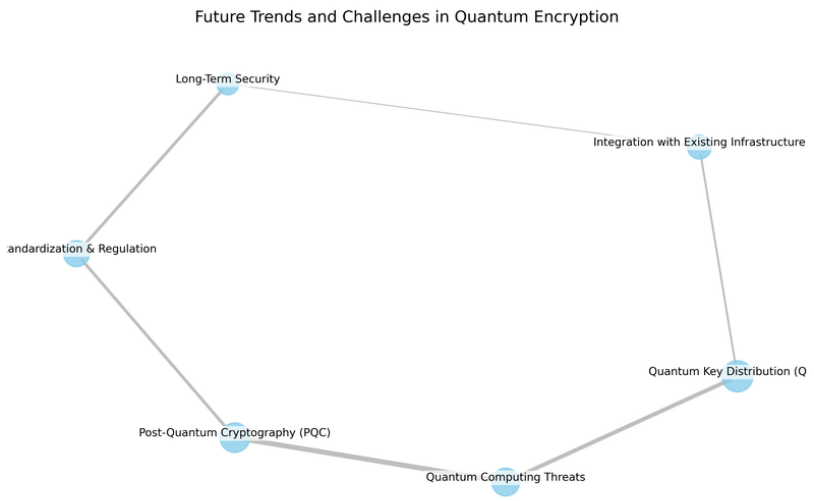

Figure: Visual representation of Future Trends and Challenges in Quantum Encryption

Future Trends and Challenges in Quantum Encryption

The advent of quantum computing presents a fundamental challenge to the security of our digital infrastructure, particularly concerning encryption [2]. While practical, large-scale quantum computers capable of breaking current encryption algorithms aren’t yet a reality, the cryptographic community is already engaged in a proactive race to develop defenses [4]. This section will explore the future trends and challenges in quantum encryption, examining both the promise of quantum solutions and the more immediate need for post-quantum cryptography (PQC). Are we truly prepared for "Q-Day," the point at which current encryption becomes obsolete [4]?

The primary threat stems from the potential of quantum computers to efficiently execute Shor's algorithm, which can break widely used public-key encryption schemes like RSA and ECC [2, 4]. This vulnerability necessitates a shift toward PQC, which focuses on developing cryptographic algorithms resistant to attacks from both classical and quantum computers [2]. Candidates for PQC include lattice-based cryptography, code-based cryptography, multivariate

cryptography, and hash-based cryptography [2]. However, these alternatives are not without their own challenges.

One significant area of focus is the rigorous analysis of PQC candidates to ensure their long-term resilience against evolving quantum algorithms [12]. We must ask ourselves, are these new algorithms truly secure, or are we simply shifting the problem to a new, yet-to-be-discovered vulnerability? NIST’s release of the first three finalized PQC standards in 2024 represents a major milestone, offering finalized encryption algorithms ready for immediate implementation [4, 5]. These standards include not only the algorithms' computer code but also detailed implementation instructions and intended use cases, facilitating a smoother transition for system administrators [5]. Furthermore, organizations are being encouraged to begin transitioning to these new standards without delay [5]. This proactive adaptation is critical to maintaining security in the face of rapidly advancing quantum computing technology [5].

Interestingly, the quantum threat primarily targets public-key cryptography [4]. Symmetric cryptographic algorithms and hash functions are considered relatively resistant; while Grover's algorithm offers a speedup in attacking symmetric ciphers, simply doubling the key size provides adequate mitigation [4]. Therefore, future trends in symmetric cryptography are expected to largely build upon existing foundations [4]. The core challenge, and thus the focus of future research, lies in developing and deploying robust, standardized, and efficient post-quantum replacements for current public-key infrastructure [4].

Beyond the development of new algorithms, the practical implementation of PQC presents its own set of hurdles. As Mikidana points out, future-proofing cybersecurity strategies requires adaptable security measures capable of defending against both existing and emerging threats [13]. This includes adopting a Zero Trust architecture, investing in scalable and modular security solutions, and leveraging AI and ML to proactively identify and predict emerging threats [13]. Moreover, continuous education and training are vital components of a robust security posture, fostering a culture of security awareness among employees and reducing the risk of human error [11, 13].

Another potential solution lies in quantum encryption, specifically quantum key distribution (QKD) [7]. QKD offers theoretically unbreakable security by leveraging the principles of quantum mechanics to distribute encryption keys. However, QKD is not a panacea. Current limitations include the limited range of QKD systems due to signal loss in fiber optic implementations, as well as the cost of implementing and maintaining QKD infrastructure [7]. Research is focused on developing quantum repeaters to extend transmission distances, improving the efficiency and security of single-photon detectors, and designing more robust QKD protocols that are resilient to real-world imperfections [7]. Hybrid approaches, combining QKD with classical cryptographic methods, are also gaining traction [7].

Furthermore, the gradual erosion of security effectiveness, known as "security drift," poses a significant concern [11]. Regular security audits, both internal and external, are essential for identifying weaknesses in an organization's security framework [11]. Audit frequency should be tailored to the organization's risk profile, with high-risk industries potentially requiring more frequent audits [11]. It is crucial to recognize that even the most advanced cryptographic solutions, like those based on quantum principles, are vulnerable to security drift if not supported by a robust and evolving security ecosystem [11].

However, the path forward is not without its challenges. The development of quantum computers themselves faces significant technical hurdles. Qubit decoherence, the loss of qubits' quantum properties due to environmental disturbances, remains a major obstacle [9, 10]. Overcoming decoherence necessitates exploration of novel materials, innovative computational methodologies, and a thorough investigation of various quantum approaches [10]. Scalability also presents a critical challenge; scaling these systems to hundreds or thousands of qubits while maintaining high coherence and low error rates represents a substantial engineering and materials science problem [9, 10].

In conclusion, securing our digital future against the threat of quantum computing requires a multifaceted approach. This includes the continued development and standardization of PQC algorithms, the exploration of quantum encryption technologies like QKD, and

the implementation of proactive cybersecurity strategies that address security drift and promote long-term resilience. The transition to a post-quantum world will be a complex and ongoing process, requiring collaboration between researchers, industry, and government to ensure a secure and prosperous future. While there are challenges ahead, the proactive measures being taken offer a degree of optimism that we can navigate this transition successfully.

Conclusion

In this exploration of quantum computing and its impact on encryption, we have traversed a landscape both promising and fraught with challenges. Our analysis began by establishing the foundational threat posed by Shor's algorithm, a quantum algorithm capable of efficiently factoring large numbers, thereby undermining the security of widely used public-key cryptosystems like RSA. As we detailed, the potential realization of a fault-tolerant quantum computer capable of executing Shor's algorithm presents a genuine existential risk to much of our current digital infrastructure. This is not merely a theoretical concern; the implications for e-commerce, secure communications, and national security are profound, demanding proactive and multifaceted responses.

However, the narrative is not one of impending cryptographic doom. As we moved beyond the threat, we examined Quantum Key Distribution (QKD), a revolutionary approach leveraging the principles of quantum mechanics to guarantee secure key exchange. QKD offers a tantalizing prospect: theoretically unbreakable encryption based on the laws of physics, rather than the computational hardness assumptions that underpin classical cryptography. Indeed, QKD's inherent security promises a future where secure communication remains possible even in a world populated by powerful quantum computers. The academic literature, as highlighted in our introduction, consistently underscores the transformative potential of QKD, positioning it as a cornerstone of post-quantum cryptography.

Synthesizing these seemingly disparate findings—the threat of Shor's algorithm and the promise of QKD—reveals a complex and nuanced picture. On one hand, the vulnerability of existing cryptographic

methods to quantum attacks necessitates a rapid and comprehensive transition to post-quantum cryptography. On the other hand, QKD offers a viable, albeit not universally applicable, solution for certain critical communication channels. It is critical to understand that QKD is not a panacea; its limitations in terms of range, cost, and infrastructure requirements mean it will likely coexist with other post-quantum cryptographic solutions.

Our exploration also delved into the future trends and challenges in quantum encryption. While QKD is maturing, significant hurdles remain. The development of cost-effective, long-range QKD systems is crucial for widespread adoption. Furthermore, the security of QKD implementations must be rigorously scrutinized to guard against side-channel attacks and imperfections in hardware. As noted in our section on future trends, research into measurement-device-independent QKD (MDI-QKD) and twin-field QKD offers promising avenues for enhancing the security and range of QKD systems.

However, our investigation also revealed limitations within current research. Much of the existing literature focuses either on the theoretical aspects of quantum algorithms and cryptography or on the practical implementation of QKD systems. There is a relative dearth of research addressing the crucial middle ground: the integration of QKD into existing network infrastructure, the development of hybrid quantum-classical cryptographic protocols, and the assessment of the economic and societal impacts of transitioning to a post-quantum world. Furthermore, the standardization of post-quantum cryptographic algorithms is a critical, ongoing process, and more research is needed to ensure that these algorithms are robust, efficient, and widely accepted.

In light of these limitations, we suggest several specific directions for future research. First, there is a pressing need for more research into hybrid cryptographic systems that combine the strengths of classical and quantum cryptography. Such systems could provide a graceful and cost-effective transition to a post-quantum world. Second, research should focus on developing quantum-resistant alternatives to existing hash functions and digital signature schemes, which are essential for ensuring the integrity and authenticity of digital information. Third, more attention should be paid to the security of QKD implementations, with a particular focus on mitigating side-

channel attacks and hardware imperfections. Finally, interdisciplinary research is needed to assess the economic, social, and ethical implications of quantum computing and its impact on encryption.

Ultimately, the advent of quantum computing represents a paradigm shift in the field of cryptography. It necessitates a fundamental rethinking of how we secure our digital information. While the challenges are significant, the opportunities are equally compelling. By embracing innovation, fostering collaboration, and investing in research, we can navigate this transition and ensure that our digital infrastructure remains secure in the face of the quantum threat. Personally, I find the potential of QKD to fundamentally reshape our understanding of secure communication incredibly exciting. The journey towards a post-quantum world will undoubtedly be complex and challenging, but it is a journey we must undertake to safeguard our digital future. The broader implications extend beyond mere technological advancement; they touch upon fundamental questions of privacy, security, and trust in an increasingly interconnected world.

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Learned From Resources

The following resources provided context and background information that informed our analysis, although they are not cited directly in the academic references:

- Wikipedia: Wikipedia - Shor's Algorithm and Its Impact on Cryptography
- Wikipedia: https://en.wikipedia.org/wiki/Shor%27s_algorithm
- Web resource: https://www.quera.com/glossary/shors-algorithm
- Web resource: https://www.amarchenkova.com/posts/break-rsa-encryption-with-this-one-weird-trick
- Organization resource: https://www.techrxiv.org/users/708580/articles/693052-implementation-and-analysis-of-shor-s-algorithm-to-break-rsa-cryptosystem-security
- Web resource: https://www.reddit.com/r/cryptography/comments/vnkz6m/what*is*stopping*shors*algorithm*from*being_used/
- Organization resource: https://eprint.iacr.org/2017/598.pdf
- Wikipedia: Wikipedia - Introduction to Quantum Computing

- Web resource: https://aws.amazon.com/what-is/quantum-computing/
- Web resource: https://www.ibm.com/think/topics/quantum-computing
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