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The Transition from Classical to Post-Quantum Cryptography
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Abstract

Quantum computing is the study of computers that use quantum features in calculations. For over 20 years, it has been known that if very large, specialized quantum computers could be built, they could have a devastating effect on asymmetric classical cryptographic algorithms such as RSA and elliptic curve signatures and key exchange, as well as (but in smaller scale) on symmetric cryptographic algorithms such as block ciphers, MACs, and hash functions. There has already been a great deal of study on how to create algorithms that will resist large, specialized quantum computers, but so far, the properties of those algorithms make them onerous to adopt before they are needed.

Small quantum computers are being built today, but it is still far from clear when large, specialized quantum computers will be built that can recover private or secret keys in classical algorithms at the key sizes commonly used today. It is important to be able to predict when large, specialized quantum computers usable for cryptanalysis will be possible so that organization can change to post-quantum cryptographic algorithms well before they are needed.

This document describes quantum computing, how it might be used to attack classical cryptographic algorithms, and possibly how to predict when large, specialized quantum computers will become feasible.

Status of This Memo

This Internet-Draft is submitted in full conformance with the provisions of BCP 78 and BCP 79.

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This Internet-Draft will expire on February 15, 2018.

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1. Introduction

Early drafts of this document use "@@@@@" to indicate where the editor particularly want input from reviewers. The editor welcomes all types of review, but the areas marked with "@@@@@" are in the most noticeable need of new material. (The editor particularly appreciates new material that comes with references that can be included in this document as well.)

1.1. Disclaimer

**** This is an early version of this draft. **** As such, it has had little in-depth review in the cryptography community. Statements in this document might be wrong; given that the entire document is about cryptography, those wrong statements might have significant security problems associated with them.

Readers of this document should not rely on any statements in this version of this draft. As the draft gets more input from the cryptography community over time, this disclaimer will be softened and eventually eliminated.

1.2. Executive Summary

The development of quantum computers that can recover private or secret keys in classical algorithms at the key sizes commonly used today is at a very early stage. None of the published examples of such quantum computers is useful in recovering keys that are in use today. There is a great amount of interest in this development, and researchers expect large strides in this development in the coming decade.

There is active research in standardizing signing and key exchange algorithms that will withstand attacks from large, specialized quantum computers. However, all those algorithms to date have very large keys, very large signatures, or both. Thus, there is a large sustained cost in using those algorithms. Similarly, there is a large cost in being surprised about when quantum computers can cause damage to current cryptographic keys and signatures.

Because the world does not know when large, specialized quantum computers that can recover cryptographic keys will be available, organizations should be watching this area so that they have plenty of time to either change to larger key sizes for classical cryptography or to change to post-quantum algorithms. See Section 6 for a fuller discussion of determining how to predict when quantum computers that can harm current cryptography might become feasible.

1.3. Terminology

The term "classical cryptography" is used to indicate the cryptographic algorithms that are in common use today. In particular, signature and key exchange algorithms that are based on the difficulty of factoring numbers into two large prime numbers, or are based on the difficulty of determining the discrete log of a large composite number, are considered classical cryptography.

The term "post-quantum cryptography" refers to the invention and study of cryptographic mechanisms in which the security does not rely on computationally hard problems that can be efficiently solved on quantum computers. This excludes systems whose security relies on factoring numbers, or the difficulty of determining the discrete log of one group element with respect to another.

Note that these definitions apply to only one aspect of quantum computing as it relates to cryptography. It is expected that quantum computing will also be able to be used against symmetric key cryptography to make it possible to search for a secret symmetric key using far fewer operations than are needed using classical computers (see Section 5 for more detail). However, using longer keys to thwart that possibility is not normally called "post-quantum cryptography".

There are many terms that are only used in the field of quantum computing, such as "qubit", "quantum algorithm", and so on. Chapter 1 of [NielsenChuang] has good definitions of such terms.

Some papers discussing quantum computers and cryptanalysis say that large, specialized quantum computers "break" algorithms in classical cryptography. This paper does not use that terminology because the algorithms' strength will be reduced when large, specialized quantum computers exist, but not to the point where there is an immediate need to change algorithms.

The "^" symbol is used to indicate "the power of". The term "log" always means "logarithm base 2".

1.4. Not Covered: Post-Quantum Cryptographic Algorithms

This document discusses when an organization would want to consider using post-quantum cryptographic algorithms, but definitely does not delve into which of those algorithms would be best to use. Post-quantum cryptography is an active field of research; in fact, it is much more active than the study of when we might want to transition from classical to post-quantum cryptography.

Readers interested in post-quantum cryptographic algorithms will have no problem finding many articles proposing such algorithms, comparing the many current proposals, and so on. An excellent starting point is the web site <http://pqcrypto.org/>. The Open Quantum Safe (OQS) project <https://openquantumsafe.org/> is developing and prototyping quantum-resistant cryptography. Another is the article on post-quantum cryptography at Wikipedia: <https://en.wikipedia.org/wiki/Post-quantum_cryptography>.

Various organizations are working on standardizing the algorithms for post-quantum cryptography. For example, the US National Institute of Standards and Technology (commonly just called "NIST") is holding a competition to evaluate post-quantum cryptographic algorithms. NIST's description of that effort is currently at <http://csrc.nist.gov/groups/ST/post-quantum-crypto/>. Until recently, ETSI (the European Telecommunications Standards Institute) had a Quantum-Safe Cryptography (QSC) Industry Specification Group (ISG) that worked on specifying post-quantum algorithms; see <http://www.etsi.org/technologies-clusters/technologies/quantum-safe-cryptography> for results from this work.

1.5. Not Covered: Quantum Cryptography

Other than in this section, this document does not cover "quantum cryptography". The field of quantum cryptography uses quantum effects in order to secure communication between users. Quantum cryptography is not related to cryptanalysis. The best known and extensively studied example of quantum cryptography is a quantum key exchange, where users can share a secret key while preventing an eavesdropper from obtaining the key.

1.6. Where to Read More

There are many reasonably accessible articles on Wikipedia, notably the overview article at <https://en.wikipedia.org/wiki/Quantum_computing> and the timeline of quantum computing developments at <https://en.wikipedia.org/wiki/Timeline_of_quantum_computing>.

[NielsenChuang] is a well-regarded college textbook on quantum computers. Prerequisites for understanding the book include linear algebra and some quantum physics; however, even without those, a reader can probably get value from the introductory material in the book.

[Turing50Youtube] is a good overview of the near-term and longer-term prospects for designing and building quantum computers; it is a video of a panel discussion by quantum hardware and software experts given at the ACM's Turing 50 lecture.

@@@@@ Maybe add more references that might be useful to non-experts.

2. Brief Introduction to Quantum Computers

A quantum computer is a computer that uses quantum bits (qubits) in quantum circuits to perform calculations. Quantum computers also use classical bits and regular circuits: most calculations in a quantum computer are a mix of classical and quantum bits and circuits. For example, classical bits could be used for error correction or controlling the behavior of physical components of the quantum computer.

A basic principle that makes it possible to speed up calculations on qubits in quantum computers is quantum superposition. Informally, similarly to waves in classical physics, arbitrary number of quantum states can be added together and result will be another valid quantum state. That means that, for example, two qubits could be in any quantum superposition of four states, three qubits in quantum superposition of eight states, and so on. Generally n qubits can be in quantum superposition of 2^n states.

The main challenge for quantum computing is to create and maintain a significantly large number of superposed qubits while performing quantum computations. Physical components of quantum computers that are non-ideal results in the destruction of qubit state over time; this is the source of errors in quantum computation. See Section 3.1 for a description of how to overcome this problem.

A good description of different aspects of calculations on quantum computer could be found in [EstimatingPreimage].

A separate question is a measurement of a quantum state. Due to uncertainty of the state, the measurement process is stochastic. That means that in order to get the correct measurement one should run several consequent calculations and corresponding measurement in order to the expected value which is considered as a result of measurement.

@@@@@ Discuss measurements and how they have to be done with correlated qubits.

2.1. Quantum Computers that Recover Cryptographic Keys

Quantum computers are expected to be useful in the future for some problems that take up too many resources on a large classical computer. However, this document only discusses how they might recover cryptographic keys faster than classical computers. In order to recover cryptographic keys, a quantum computer needs to have a quantum circuit specifically designed for the type of key it is attempting to recover.

A quantum computer will need to have a circuit with thousands of qubits to be useful to recover the type and size keys that are in common use today. Smaller quantum computers (those with fewer qubits in superposition) are not useful for using Shor's algorithm (as discussed in Section 4.1) at all. That is, no one has devised a way to combine a bunch of smaller quantum computers to perform the same attacks on cryptographic keys via Shor's algorithm as a properly-sized quantum computer.

This is why this document uses the term "large, specialized quantum computer" when describing ones that can recover keys: there will certainly be small quantum computers built first, but those computers cannot recover the type and size keys that are in common use today. Further, there are already quantum computers that have many qubits but without the circuits needed to make those qubits useful for recovering cryptographic keys.

A straight-forward application of Shor's algorithm may not be the only way for large, specialized quantum computers to attack RSA keys. [LowResource] describes how to combine quantum computers with classical methods for recovering RSA keys at speeds faster than just using the classical methods.

3. Physical Designs for Quantum Computers

Quantum computers can be built using many different physical technologies. Deciding which physical technologies are best to pursue is an extremely active research topic. A few physical technologies (particularly trapped ions, super-conduction using Josephson junctions, and nuclear magnetic resonance) are currently getting the most press, but other technologies are also showing promise.

One factor that is important to quantum computers that can be used for cryptanalysis is the speed of the operations (transformations) on

qubits. Most of the estimates of speeds of these quantum computers assume that qubit operations will take about the same amount of time as operations in circuits that consist of classical gates and classical memory. Current quantum circuits are slower than classical circuits, but will certainly become faster as quantum computers are developed in the future.

Note that some current quantum computer research uses bits that are not fully entangled, and this will greatly affect their ability to make useful quantum calculations.

3.1. Qubits, Error Detection, and Error Correction

Researchers building small quantum computers have discovered that calculating the superposition of qubits often has a large rate of error, and that error rate increases rapidly over time. Performing quantum calculations such as those needed to recover cryptographic keys is not feasible with the current state of quantum computers.

In the future, actual quantum calculations will be performed on "logical qubits", that is, after the application of error correction codes on physical qubits. Thus, the number of physical qubits will be higher than the number of logical qubits, depending on the parameters of the error correction code, which in turn depends on the parameters of a technology used for a physical implementation of qubits. Currently, it is estimated that it takes hundreds or thousands of physical qubits to make a logical qubit. @@@@@ Need reference for this statement.

@@@@@ Lots more material should go here. We will need recent references for how many physical qubits are needed for each corrected qubit. It's OK if this section has lots of references, but hopefully they don't contradict each other.

3.2. Promising Physical Designs for Quantum Computers

@@@@@ It would be useful to have maybe two paragraphs about each physical design that is being actively pursued.

3.3. Challenges for Physical Designs

Different designs have different challenges to overcome before the physical technology can be scaled enough to build a useful large, specialized quantum computer. Some of those challenges include the following. (Note that some items on this list apply only to some of the physical technologies.)

Temperature: Getting stable operation without extreme cooling is difficult for many of the proposed technologies. The definition of "extreme" is different for different low-temperature technologies.

Stabilization: The length of time every qubit in a circuit holds is value

Quantum control: Coherence and reproducibility of qubits

Error detection and correction: Getting accurate results through simultaneous detection of bit-flip and phase-flip. See Section 3.1 for a longer description of this.

Substrate: The material on which the qubit circuits are built. This has a large effect on the stability of the qubits.

Particles: The atoms or sub-atomic particles used to make the qubits

Scalability: The ability to handle the number of physical qubits needed for the desired the circuit

Architecture: Ability to change quantum gates in a circuit

4. Quantum Computers and Public Key Cryptography

The area of quantum computing that has generated the most interest in the cryptographic community is the ability of quantum computers to find the private keys in encryption and signature algorithms based on discrete logarithms using exponentially fewer operations than classical computers would need to use.

As described in [RFC3766], it is widely believed that factoring large numbers and finding discrete logs using classical computers increases with the exponential size of the key. [RFC3766] describes in detail how classical computers can be used to determine keys; even though that RFC is over a decade old, no significant changes have been made to the process of classical attacks on RSA and Diffie-Hellman. @@@@@ CFRG: is that true? Does RFC 3766 need to be updated?

Shor's algorithm shows that these problems can be solved on quantum computers in polynomial time, meaning that the speed of finding the keys is a polynomial function (with reasonable-sized coefficients) based on the size of the keys, which would require significantly fewer steps than a classical computer. The definitive paper on Shor's algorithm is [Shor97].

4.1. Explanation of Shor's Algorithm

@@@@@ Pointers to understandable articles would be good here.

@@@@@ Describe period-finding and why it applies to finding prime factors and discrete logs.

@@@@@ Give the steps for applying Shor's algorithm to 2048-bit RSA. Describe how many rounds of the quantum subroutine would likely be needed. Describe how many rounds of the classical loop would likely be needed.

[ResourceElliptic] gives concrete estimates of the resources needed to build a quantum computer to compute elliptic curve discrete logarithms. It shows that for the common P-256 elliptic curve, 2330 logical qubits and over 10^11 Toffoli gates.

4.2. Properties of Large, Specialized Quantum Computers Needed for Recovering RSA Public Keys

Researchers have built small quantum computers that implement Shor's algorithm, factoring numbers with four or five bits. These are used to show that Shor's algorithm is possible to realize in actual hardware. (Note, however, that [PretendingFactor] indicates that these experiments may have taken shortcuts that prevent them from indicating real Shor designs.)

@@@@@ References are needed here. Did they implement all of Shor's algorithm, including the looping logic in the classical part and the looping logic in the quantum part?

@@@@@ Numbers and explanation is needed below:

A quantum computer that can determine the private keys for 2048-bit RSA would require SOME NUMBER GOES HERE correlated qubits and SOME NUMBER GOES HERE circuit elements. A quantum computer that can determine the private keys for 256-bt elliptic curves would require SOME NUMBER GOES HERE correlated qubits and SOME NUMBER GOES HERE circuit elements.

5. Quantum Computers and Symmetric Key Cryptography

Section 4 is about Shor's algorithm and compromises to public key cryptography. There is a second quantum computing algorithm, Grover's algorithm, that is often mentioned at the same time as Shor's algorithm. With respect to cryptanalysis, however, Grover's algorithm applies to tasks of finding a preimage, including tasks of finding a secret key of a symmetric algorithm such as AES if there is

knowledge of plaintext-ciphertext pairs. The definitive paper on Grover's algorithm is by Grover: [Grover96]. Grover later wrote a more accessible paper about the algorithm in [QuantumSearch].

Grover's algorithm gives a way to search for keys to symmetric algorithms in the square root of the time that a normal exhaustive search would take. Thus, a large, specialized quantum computer that implements Grover's algorithm could find a secret AES-128 key in about 2^64 steps instead of the 2^128 steps that would be required for a classical computer.

When it appears that it is feasible to build a large, specialized quantum computer that can defeat a particular symmetric algorithm at a particular key size, the proper response would be to use keys with twice as many bits. That is, if one is using the AES-128 algorithm and there is a concern that an adversary might be able to build a large, specialized quantum computer that is designed to attack AES-128 keys, move to an algorithm that has keys twice as long as AES-128, namely AES-256 (the block size used is not significant here).

It is currently expected that large, specialized quantum computers that implement Grover's algorithm are expected to be built long before ones that implement Shor's algorithm are. There are two primary reasons for this:

- Grover's algorithm is likely to be useful in areas other than cryptography. For example, a large, specialized quantum computer that implements Grover's algorithm might help create medicines by speeding up complex problems that involve how proteins fold. @@@@@ Add more likely examples and references here.

- A large, specialized quantum computer that can recover AES-128 keys will likely be much smaller (and thus easier to build) than one that implements Shor's algorithm for 256-bit elliptic curves or 2048-bit RSA/DSA keys.

5.1. Explanation of Grover's Algorithm

@@@@@ Give the steps for applying Grover's algorithm to AES-128.

5.2. Properties of Large, Specialized Quantum Computers Needed for Recovering Symmetric Keys

[ApplyingGrover] estimates that a quantum computer that can determine the secret keys for AES-128 would require 2953 correlated qubits and 2.74 * 2^86 gates.

5.3. Properties of Large, Specialized Quantum Computers for Computing Hash Collisions

@@@@@ More goes here. Also, discuss how Grover's algorithm does not appear to be useful for computing preimages (or say how it might be used.

6. Predicting When Useful Cryptographic Attacks Will Be Feasible

If quantum computers that perform useful cryptographic attacks can be built in the future, many organizations will want to start using post-quantum algorithms well before those computers can be built. However, given how few implementations of such quantum computers exist (even for tiny keys), it is impossible to predict with any accuracy when quantum computers that perform useful cryptographic attacks will be feasible.

The term "useful" above is relative to the value of the material being protected by the cryptographic algorithm to the attacker. For example, if the quantum computer attacking a particular key costs US$100 billion to build, costs US$1 billion a year to run, and can extract only one key a year, it is possibly useful to some governments, but probably not useful for attacking the TLS key used to protect a small mail server. On the other hand, if later a similar computer costs US$1 billion to build, costs US$10 million a year to run, and can extract ten keys a year, many more keys become vulnerable.

[BeReady] gives a simple way to approach the calculation of when one needs to deploy post-quantum algorithms. In short, if the sum of how long you need your keys to be secure plus how long it takes to deploy new algorithms is longer than the length of time it will take for an attacker to create a large, specialized quantum computer and use it against your keys, then you waited too long.

To date, few people have done systematic research that would give estimates for when useful quantum-based cryptographic attacks might be feasible, and at what cost. Without such research, it is easy to make wild guesses but those are not of much value to people having to decide when to start using post-quantum cryptography.

For example, in [NIST8105], NIST says "researchers working on building a quantum computer have estimated that it is likely that a quantum computer capable of recovering 2000-bit RSA in a matter of hours could be built by 2030 for a budget of about a billion dollars". However, the referenced link is to a YouTube video [MariantoniYoutube] where the researcher, Matteo Mariantoni, says "maybe you should not quote me on that". [NIST8105] gives no other

references for predictions on cost and availability of useful cryptographic attacks with quantum computers.

6.1. Proposal: Public Measurements of Various Quantum Technologies

In order to get a rough idea of when useful cryptographic attacks with quantum computers may be feasible, researchers creating such computers can demonstrate them when they can recover keys an eighth the size of those in common use. That is, given that 2048-bit RSA, 256-bit elliptic curve, and AES-128 are common today, when a research team has a computer than can recover 256-bit RSA, 32-bit elliptic curve, or AES-128 where only 16 bits are unknown, they should demonstrate it.

Such a demonstration could easily be made fair with trusted representatives from the cryptographic community using verifiable means to pick the keys to recover, and verifying the time that it takes to recover each key. It might be interesting to run the same tests in classical computers at the same time to give perspective.

These demonstrations will have many benefits to those who have to decide when post-quantum algorithms should be deployed in various environments.

- Demonstrations will likely use designs that are considered most efficient. This in turn will cause greater focus research on choosing good design candidates.

- The results of the demonstrations will help focus on issues important to cryptanalysis, namely the cost of building the systems and the speed of breaking a single key.

- Competing demonstrations will reveal where different research teams have made different optimizations from well-known designs.

- Public demonstrations could expose designs that work only in limited cases that are uncommon in normal cryptographic practice. (For example, [PretendingFactor] claims that all current factorization experiments have taken advantage of using a classical computer that already knows the answer to design the quantum circuits.)

Note that this proposal would only give an idea of how public progress is being made on quantum computers. Well-funded military agencies (and possibly even criminal enterprises) could be way ahead of the publicly-visible computers. No one should rely on just the public measurements when deciding how safe their keys are against quantum computers.

7. IANA Considerations

None, and thus this section can be removed at final publication.

8. Security Considerations

This entire document is about cryptography, and thus about security.

See Section 1.1 for an important disclaimer about this document and security.

This document is meant to help the reader predict when to transition from using classical cryptographic algorithms to post-quantum algorithms. That decision is ultimately up to the reader, and must be made not only based on predictions of how quantum computing is progressing but also the value of every key that the user handles. For example, a financial institution using TLS to protect its customers' transactions will probably consider its keys more valuable than a small online store, and will thus be likely to begin the transition earlier.

9. Acknowledgements

The list here is meant to acknowledge input to this document. The people listed here do not necessarily agree with ideas presented.

Many sections of text were contributed by Grigory Marshalko and Stanislav Smyshlyaev.

Some of the ideas in this document come from Denis Butin, Philip Lafrance, Hilarie Orman, and Tomofumi Okubo.

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