Cybersecurity in an era with quantum computers: will we be ready?

Michele Mosca*

Institute for Quantum Computing and Department of Combinatorics and Optimization, University of Waterloo, Waterloo, Ontario , Canada

Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada

Canadian Institute for Advanced Research, Toronto, Ontario, Canada

1 The Problem

Cyber technologies are becoming an increasingly important part of all facets of our lives. Consequently, cybersecurity is a fundamental and growing part of what it means for us to be safe. One of the most fundamental pillars of cybersecurity is cryptography. Most of the cryptography tools we use today rely on computational assumptions, such as the hardness of factoring 2048 bit numbers. These computational problems are sometimes broken (e.g. [Tut00], [BFMV84], [FMS01], [WY05]) by algorithmic advances or increased computing power.

Two decades ago, we learned that the quantum paradigm implies that essentially all the deployed public key cryptography will be completely broken by a quantum computer [Sho94] and that brute force attacks of symmetric ciphers can also be sped up by roughly a quadratic factor [Gro96, BBHT98].

Most new paradigms are not initially greeted with great acceptance, as described nicely in the Max Planck quote [Kuh70]: "A new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it." There has been much skepticism about the prospect of a large scale quantum computer in the forseeable future (or ever) capable of implementing Shor's algorithms or quantum searching. People naturally ask if they can continue to delay taking action, since there are many other urgent and serious matters at hand. Whether one can continue to delay roughly depends on three questions.

Firstly, how long do you need your cryptographic keys to be remain secure? Denote this number by x. We may have $x = 0$ years for applications requiring only real-time security. Or maybe $x = 10, 20, 100$ years when protecting your personal health information, trade secrets, or national security information. The value of x is in general a personal or business or policy decision.

Next, how long will it take to deploy a set of tools that are quantum-safe? Denote this number by y.

Lastly, how long will it be before a quantum computer, or some other method, breaks the currently deployed public-key cryptography tools? Let z denote this number.

If $x+y > z$, we have a serious problem today [Mos13] , since information protected by quantum-vulnerable tools at the end of the next y years can be broken by quantum attacks in less than x years from then.

So what is z? In 2011, colleagues at IBM [SDCTK11] stated "Rapid improvements in experimental quantum hardware suggest that a threshold for the design and the construction of fault-tolerant systems may be reached in the next five years". Colleagues at Yale [DS13] nicely laid out seven stages to building a large-scale quantum computer, and report that several implementations, including superconducting qubits, have reached stage 3 and are working on stage 4. Impressive developments toward reaching stage 4 continue worldwide (e.g. [CMS+15] [RPH+15] [KBF+15]). The last 3 stages will involve an intense focused engineering effort to scale fault-tolerant designs of quantum computing systems. While it is hard to predict how long these final stages will take, there is no reason for cybersecurity experts to be confident that it will take much more than a decade or so.

At present, I estimate a 1/7 chance of breaking RSA-2048 by 2026 and a 1/2 chance by 2031. Very recently, the NSA has announced preliminary plans for transitioning to quantum resistant algorithms [NSA15].

*mmosca@uwaterloo.ca
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2 The solutions

There are two complementary families of possible solutions.

One family of solutions is sometimes known as post-quantum cryptography, and refers to conventional ciphers based on mathematical problems other than factoring and discrete logarithms, and that we believe are secure against quantum attack. These solutions have the convenience of working on conventional hardware. With these solutions we are still in the situation of computational security based on the hypothesized hardness of some problem.

Another family of solutions is known as quantum cryptography. A downside is that one needs a quantum channel – a means for sending quantum bits between locations. While in the short term, such quantum channels are available from point to point over relatively short distances, in the medium and long term satellite quantum communication and quantum repeaters will enable global distance QKD. A big advantage is that there are no computational assumptions.

It is very important to emphasize that the cryptographic ecosystem is strongest if and when both families of solutions are available. For example, some users will benefit from "good enough" security at lower cost, while others will appreciate a highly reliable method for providing long-term confidentiality. Furthermore, together they can achieve security tools with useful properties that can cannot be achieved by either family of solutions on its own. For example [IM12], one can use post-quantum signatures based on hash-functions together with QKD-based key establishment in order to obtain, in a public-key setting, cryptographic keys that are cryptographically unbreakable provided that the hash-function used is not broken at the time the key is established. The only known way to achieve this with only conventional cryptography, without adding additional assumptions (like bounded memory assumptions), is to use public-key encryption to establish the keys. In this case, for the keys to remain secure, the public-key encryption must not be broken. Complexity theory gives us much greater confidence in the short-term security of a hash function than in the long-term security of a public-key encryption scheme (which requires more mathematical structure).

While in principle we have solutions, how ready are we to quantum-proof in practice? What is y? Can we do this quickly or will it take decades?

3 Next steps

A wide range of research, ranging from fundamental to applied, still needs to be done to take QKD from its current state to one where it is a widely deployed global solution that can be reliably certified and be a part of major standards. In the short term, it is a feasible point-to-point and trusted repeater solution that organizations may take advantage of (in addition to the best available conventional cryptography) in order to have the most secure quantum-safe cryptography solutions available today. While this potential market may be relatively small at present, it will grow immensely once satellite QKD and untrusted quantum repeaters are widely deployed. It is important that we design the next-generation cryptography standards to be compatible with these solutions.

Post-quantum cryptography also requires a wide range of research from fundamental studies of their resistance to quantum attacks, to studies of their efficiencies under various resources constraints, to studies of their side-channel resistance.

Practical deployments of both quantum and post-quantum cryptography sooner rather than later will enable the applied cryptography and security community to battle-test these solutions under real-world conditions and better prepare them for "show-time" when the current cryptography tools are no longer able to provide the required security.

Appropriate standards and practices will need to be in place, and it has been encouraging to see major standards organizations such as ETSI, NIST, NICT, and IETF involved in the quantum-safe cryptography space for a number of years.

We will also need a new generation of cryptographers who understand how conventional cryptography works, who understand the landscape of the quantum-safe cryptography options, and who understand how to take new cryptography tools into practical applications.

We are still many years away from the widespread deployment of reliable quantum-safe cryptography. There is no quick fix and we cannot quickly make up lost time. While a large-scale quantum computer is a medium-term threat, given the wide and deep range of work to be done in order to widely deploy quantum-safe cryptography in practice, it is unfortunately not clear that $y < z$.

Despite the many technical and scientific challenges to deploying quantum-safe cryptography, the main challenges in my opinion are the business and policy decisions that would drive the adoption of quantum-safe cryptography. If we have an opportunity to inform and influence such decisions, this would be very helpful. For example, one can ask people and organizations to articulate their plan for managing the risk associated with the quantum threat.

Harnessing the power of quantum mechanics in large-scale quantum computers will allow us to solve many valuable problems for humanity, but we must first take the catastrophic impact of breaking cyber-security off the table by developing and deploying a suite a quantum-safe cryptographic tools before quantum computers arrive.

Quantum-safe cryptography is a necessary part of cybersecurity in an era with quantum computers.

There are many important and difficult research challenges we need to tackle so that we may be ready.

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