Cryptography in a Quantum World *

Gilles Brassard\textsuperscript{1,2}

\textsuperscript{1} Département d’informatique et de recherche opérationnelle
Université de Montréal, C.P. 6128, Succursale Centre-ville
Montréal (QC), H3C 3J7 Canada
\textsuperscript{2} Canadian Institute for Advanced Research
brassard@iro.umontreal.ca
http://www.iro.umontreal.ca/~brassard/en/

Abstract. Although practised as an art and science for ages, cryptography had to wait until the mid-twentieth century before Claude Shannon gave it a strong mathematical foundation. However, Shannon’s approach was rooted in his own information theory, itself inspired by the classical physics of Newton and Einstein. But our world is ruled by the laws of quantum mechanics. When quantum-mechanical phenomena are taken into account, new vistas open up both for codemakers and codebreakers. Is quantum mechanics a blessing or a curse for the protection of privacy? As we shall see, the jury is still out!

Keywords: Cryptography, Quantum mechanics, Quantum computation, Post-quantum cryptography, Quantum communication, Quantum key distribution, Edgar Allan Poe

1 Introduction

For thousands of years, cryptography has been an ongoing battle between codemakers and codebreakers \[1\] \cite{2}, who are more formally called cryptographers and cryptanalysts. Naturally, good and evil are subjective terms to designate codemakers and codebreakers. As a passionate advocate for the right to privacy, my allegiance is clearly on the side of codemakers. I admit that I laughed hysterically when I saw the Zona Vigilada warning that awaits visitors of the Plaça de George Orwell near City Hall in Barcelona \[3\]. Nevertheless, I recognize that codebreakers at Bletchley Park during the Second World War were definitely on the side of good. We all know about the prowess of Alan Turing, who played a key role at the routine (this word is too strong) decryption of the German Enigma cipher \[4\]. But who remembers Marian Rejewski, who actually used pure (and beautiful) mathematics to break Enigma with two colleagues before the War even started? \[5\] Indeed, who remembers except yours truly and nationalist Poles such as my friend Artur Ekert? Certainly not filmmakers! \[6\] And who remembers William Tutte, who broke the much more difficult Lorenz cipher (codenamed Tunny by the Allies), which allowed us to probe the mind of

\* Invited talk at SOFSEM 2016. Final publication available at link.springer.com.
Hitler? Tutte moved on to found the Computer Science department at the University of Waterloo, Canada, now home of IQC, the Institute for Quantum Computation, but never said a word until the 1990s about how he won the War for us. The Canadian Communications Security Establishment pays homage with its Tutte Institute for Mathematics and Computing. But who else remembers those silent heroes on the codebreaking side? I am getting carried away by emotions as I type these words while flying from Tókyó to Calgary, on my way home after the amazingly successful 5th Annual Conference on Quantum Cryptography, QCrypt 2015.

Regardless of the side to which good belongs, the obvious question is: Who will win the battle between codemakers and codebreakers? More specifically, how do the recent advances in Quantum Information Science (QIS) change this age-old issue? Until the mid-twentieth century, History has taught us that codemakers, no matter how smart, have been systematically outsmarted by codebreakers, but it ain’t always been easy. For instance, le chiffre indéchiffrable, usually attributed to Blaise de Vigenère in 1585, but actually invented by Giovan Batista Belaso 32 years earlier, remained invulnerable until broken by Charles Babbage more than three centuries after its invention. (Baggage is best known for the Analytical Engine, which would have been the first programmable computer had the technology of his days been able to rise up to the challenge.) The apparent upper hand of codebreakers, despite the still enduring invulnerability of the chiffre indéchiffrable, prompted American novelist and high-level amateur cryptanalyst Edgar Allan Poe to confidently declare in 1841 that “It may be roundly asserted that human ingenuity cannot concoct a cipher which human ingenuity cannot resolve.” Poe, do I need to mention, was among other things the author of The Gold-Bug, published in June 1843. This extraordinary short story centring on the decryption of a secret message was instrumental on kindling the career of prominent cryptographers, such as William Friedman’s, America’s foremost cryptanalyst of a bygone era, who read it as a child.

Cryptography was set on a firm scientific basis by Claude Shannon, the father of information theory, as the first half of the twentieth century was coming to a close. Actually, it’s likely that his groundbreaking work was achieved several years earlier but kept classified due to the War effort. In any case, Shannon’s theory was resolutely set in the context of classical physics. In retrospect, this is odd since it was clearly established at that time that Nature is ruled not by the Laws envisioned centuries earlier by Sir Isaac Newton, and not even by those more modern of Albert Einstein, but by the counterintuitive features of the emerging quantum mechanics. Shannon was well aware of this revolution in physics, but he probably did not think it relevant to the foundations of information theory, which he developed as a purely abstract theory.

In particular, Shannon did not question the “fact” that encrypted information transmitted from a sender (codenamed Alice) to a receiver (codenamed Bob) could be copied by an eavesdropper (codenamed Eve) without causing any disturbance noticeable by Alice and Bob. From this unfounded assumption, Shannon proved a famous theorem according to which perfect secrecy requires
the availability of a shared secret key as long as the message that Alice wishes to transmit securely to Bob, or more precisely as long as the entropy of that message, and that this key cannot be reused [14]. This theorem is mathematically impeccable, but it is nevertheless irrelevant in our quantum-mechanical world since the assumption on which its proof is based does not hold.

My purpose is to investigate the issue of whether or not Poe was right in his sweeping mid-nineteenth century statement. Could it be indeed that codebreakers will continue to have the upper hand over codemakers for the rest of eternity?

2 The Case of Classical Codemakers against Classical Codebreakers

The first electronic computers were designed and built to implement Tutte’s beautiful mathematical theory on how to break the high-level German code during World War II. They were codenamed the Colossus and ten of them were built in Bletchley Park [15]. As mentioned in the Introduction, they were instrumental in allowing us to win the War. However, in order to secure secrecy of the entire Bletchley Park operation, they were smashed to bits (funny expression when it concerns computers!) once the War was over. Consequently, I “learned” as a child that the first electronic computer in history had been the American ENIAC, when in fact it was the eleventh! Little did the pioneers of the Colossus imagine that, by an ironic twist of fate, they had unleashed the computing power that was to bring (temporary?) victory to the codemakers. In a sense, codebreakers had been the midwife of the instrument of their own destruction. Perhaps. Indeed, the rise of public-key cryptography in the 1970s had led us to believe that an increase in computing power could only be in favour of code-makers, hence at the detriment of codebreakers.

But well before all this took place, a cryptographic method that offers perfect secrecy, which later came to be known as the one-time pad, had already been invented in the nineteenth century. It is usually attributed to Gilbert Vernam, who was granted a US Patent in 1919 [16]. However, according to prime historian David Kahn, Vernam had not realized the crucial importance of never using the same key twice until Joseph Mauborgne pointed it out [1, p. 398]. But it was later discovered that the one-time pad had been invented 35 years earlier by Frank Miller, a Sacramento banker [17]. Its perfect security was demonstrated subsequently by Shannon [14]. In any case, the one-time pad requires a secret key as long as the message to be transmitted, which makes it of limited practical use. It was nevertheless used in real life, for instance on the red telephone between John Kennedy and Nikita Khruschev during the Cold War [15], as well as between Fidel Castro and Che Guevara after the latter had left Cuba for Bolivia [19]. But in our current information-driven society, we need a process by which any two citizens can enjoy confidential communication. For this, a method to establish a shared secret key is required. Could this be achieved through an authentic public channel, which offers no protection against eavesdropping?
The first breakthrough in the academic world came to Ralph Merkle in 1974, who designed a scheme capable of providing a quadratic advantage to code-makers over codebreakers. Merkle’s scheme is secure under the sole assumption (still unproven to this day) that some problems can only be solved by exhaustive search over their space of potential solutions. At the time, Merkle was a graduate student at the University of California in Berkeley, enrolled in a computer security class. Unable to make his ideas understood by his professor, Merkle “dropped the course, but kept working on the idea” [20]. After several years, he prevailed and his landmark paper was finally published [21]. However, Whitfield Diffie, a graduate student “next door”, at Stanford University, had similar ideas independently, albeit shortly after Merkle. But Diffie was lucky enough to have an advisor, Martin Hellman, who understood the genius of his student. Together, they made the concepts of public-key cryptography and digital signature immensely popular [22], two years before Merkle’s publication.

A few years later, Ronald Rivest, Adi Shamir and Leonard Adleman, inspired by the Diffie-Hellman breakthrough, proposed an implementation of public-key cryptography and digital signatures that became known to all as the RSA cryptosystem [23]. And thus, history was made. The fact that the RSA cryptosystem had in fact been invented in 1973 by Clifford Cocks [24], at the British secret services known as GCHQ, is of little relevance to the practical importance of the discovery on what was to become the Internet. As long as the factorization of large numbers remained infeasible, the codemakers had finally won the battle, proving Poe wrong. Soon, electronic safety all over the Internet revolved around this RSA cryptosystem, as well as the earlier invention known as the Diffie-Hellman key establishment protocol [22]. At about the same time, Robert McEliece invented another approach, based on error-correction codes [25], which did not come into practical use because it required much longer keys than either the RSA or the Diffie-Hellman solution. Later, the same apparent level of security was obtained with significantly shorter keys by bringing in the number-theoretic notion of elliptic curves [26,27]. And the Internet was a happy place. Or so it seemed.

End of story?

3 The Unfair but Realistic Case of Classical Codemakers against Quantum Codebreakers

End of story? Not quite! In the early 1980s, Richard Feynman [28,29] and, independently, David Deutsch [30], invented the theoretic notion of a quantum computer. This hypothetical device would use the counterintuitive features of quantum mechanics for computational purposes. At first, it was not clear that quantum computers, even if they could be built, could speed up calculations.

And then, in 1994, Peter Shor [31], and independently Alexi Kitaev [32], discovered that quantum computers have the power to factor large numbers and extract discrete logarithms efficiently, bringing to their knees not only the RSA cryptosystem but also the Diffie-Hellman key establishment scheme, even if based on elliptic curves. As a society, we are extremely fortunate that Shor’s
and Kitaev’s discoveries were made before a quantum computer had already been built for some other purposes (such as computational physics and chemistry). Quite literally, this saved civilization from catastrophic collapse. But now that we have known about the looming threat for over two decades, surely we are active at deploying solutions that have at least a fighting chance to withstand the onslaught of a quantum computer.

Well, not really. :-(

The general apathy towards the quantum threat to worldwide security on the Internet and beyond is quite simply appalling. Why react today (or more appropriately twenty years ago) when we can quietly wait for disaster? After all, no serious business model looks more than five years in the future, and it would be expensive to change the current cryptographic infrastructure. And indeed, a full-scale quantum computer is unlikely to materialize in the next five years. Except perhaps in an ultra-secret basement somewhere, be it governmental or industrial... But when (not “if”) this happens, all past communications will become insecure to whomever was wise enough to have stored the Internet traffic that was until then undecipherable. The fact that current cryptographic techniques are susceptible to being broken retroactively is their main conceptual weakness. Any secret entrusted to them today, even if it is indeed currently secure (something that we do not know how to prove), will be exposed as soon as a sufficiently large quantum computer becomes operational.

So, was Poe right after all? Are codebreakers poised to regain their upper hand? Not necessarily! Alternative encryption methods have been designed, which are not (yet) known to be vulnerable to a quantum attack, ironically including the historical McEliece approach [24], which had been scorned upon its invention because of the length of its keys. More recent approaches based on hash functions, short vectors in lattices and multivariate polynomials are being vigorously investigated. The emerging field of post-quantum cryptography is devoted to the study of (hopefully) quantum-resistant encryption [33-34]. Unfortunately, we cannot prove that any of these alternatives is secure, but at least they are not already known to be compromised by the advent of a quantum computer. Well, in the case of lattice-based cryptography [35], this is not so clear anymore [36-38]. But one thing is sure: we cannot hope to be protected by these techniques if we don’t use them! On the other hand, some of these more recent schemes could in fact be less secure than RSA against a classical attack, simply because they have not yet stood the test of time. Therefore, a transition to these new techniques should be carried out with the utmost care. But it must be carried out.

Michele Mosca likes to tell the following tale. Let $x$ denote the length of time (in years) that you want your secrets to remain secret. Let $y$ denote the time it will take to re-tool the current infrastructure with quantum-safe encryption (assuming that such a thing actually exists). Let $z$ denote the time it will take before a full-scale quantum computer is operational. Mosca’s “theorem” tells us that if $x + y > z$, then it is time to panic! Sadly, it may even be that $y > z$, meaning that it’s already too late to avoid a complete meltdown of the Internet. So, what are we waiting for?
It turns out that the American National Security Agency (NSA) is taking this threat very seriously indeed. This last August (2015), they issued a directive called “Cryptography Today” in which they announced that they “will initiate a transition to quantum resistant algorithms in the not too distant future” [39]. Most significantly, they wrote: “For those partners and vendors that have not yet made the transition to Suite B elliptic curve algorithms, we recommend not making a significant expenditure to do so at this point but instead to prepare for the upcoming quantum resistant algorithm transition”. Said plainly, even though elliptic-curve cryptography is believed to be more secure than first-generation public key solutions against classical cryptanalysis, it is no longer considered to offer sufficient long-term security under the looming threat of a quantum computer to be worth implementing at this point. It’s nice to see that someone is paying attention. For once, I’m glad that the NSA is listening! ;-

From a theoretical perspective, despite what I wrote above, it is possible to have provably quantum-safe encryption under the so-called random oracle model, which is essentially the model that was used by Merkle in his original 1974 invention of public key establishment [20]. In a classical world, this model roughly corresponds to the assumption that there are problems that can only be solved by exhaustive search over their space of potential solutions. In the quantum setting, exhaustive search can be replaced by a celebrated algorithm due to Lov Grover, which offers a quadratic speedup [40], but no more [41].

Recall that Merkle’s original idea brought a quadratic advantage to code-makers over codebreakers. But since Grover’s algorithm offers a quadratic speedup to codebreakers, this completely offsets the codemakers’ advantage. As a result, codebreakers can find the key established by codemakers in the same time it took to establish it! [42] The obvious reaction is to let the codemakers use quantum powers as well, but please remember that in this section, we consider quantum codebreakers but only classical codemakers. Nevertheless, I have discovered with Peter Høyer, Kassem Kalach, Marc Kaplan, Sophie LaPlante and Louis Salvail that Merkle’s idea can be modified in a way that if the code-makers are willing to expend an effort proportional to some parameter $N$, they can obtain a shared key that cannot be discovered by a quantum codebreaker who is not willing to expend an effort proportional to $N^{7/6}$ [43]. As I said, this is purely theoretical because it is not possible to argue that such an advantage offers practical security. Indeed, $N$ would have to be astronomical before a key that is obtained in, say, one second would require more than one year of codebreaking work. In contrast, Merkle’s quadratic advantage is significant for reasonably small values of $N$. Nevertheless, our work should be seen as a proof of principle. Now that we know that some security is possible in the unfair case of classical codemakers against quantum codebreakers, it is worth trying to do better (or prove that it is not possible).

Coming back to the question asked at the end of the Abstract, quantum mechanics appears to be a curse for the protection of privacy in this unfair context, which is hardly surprising since only codebreakers were assumed to use it!
4 Allowing Codemakers to Use Quantum Computation

The previous section considered a realistic scenario in which simple citizens want to protect their information against a much more powerful adversary. Indeed, it is likely that quantum computers will initially be available only to large governmental, industrial and criminal organizations. Furthermore, it is safe cryptographic practice to assume that your adversary is computationally more powerful (and possibly also more clever) than you are.

Nevertheless, in the more distant future, one can imagine a world in which quantum computers are as ubiquitous as classical computers are today. When this happens, codemakers will no longer be limited to classical computing. Can this restore the balance? Or even better, could the availability of quantum computers turn out to be to the advantage of codemakers, just as had been the availability of ever increasing classical computational power since the inception of public-key cryptography in the mid-1970s? Unfortuately, I am not aware of any encryption technique that would benefit from quantum computation sufficiently to offset the benefits that quantum computation would bestow on codebreakers.

For instance, it is easy to partially repair Merkle’s approach [42] if the code-makers are also allowed to use Grover’s algorithm, or more precisely a variant known as BBHT [44]. Having expended an effort proportional to $N$ in order to obtain a shared key, they can create a puzzle on which classical codebreakers would have to expend an effort proportional to $N^3$, a clear improvement over the quadratic advantage of the original classical Merkle approach. However, a quantum codebreaker would simply use Grover’s algorithm to obtain the key after an effort proportional to $N^{3/2}$. This is not a complete break, but this quantum scheme is not as secure as Merkle’s original would have been against a classical adversary. So, we see that quantum-mechanical powers have helped the codebreakers more than the codemakers. Can codemakers use quantum powers in a more clever manner? Well, we have developed a less obvious Merkle-like quantum key establishment scheme against which a quantum codebreaker needs to spend a time proportional to $N^{7/4}$ [43]. This is still not quite the quadratic advantage that was possible in an all-classical world, but it is reasonably close and possibly secure enough to be used in practice.

Nevertheless, quantum mechanics still appears to be a curse for the protection of privacy even when codemakers are also allowed to make use of it.

5 Allowing Codemakers to Use Quantum Communication

Until now, we had restricted all communication between codemakers to be classical. It turns out that quantum communication comes with a great advantage because of the no-cloning theorem [45], which says that the state of elementary particles cannot be copied even in principle. This is precisely what causes the demise of the “famous” theorem by Shannon mentioned at the end of the Introduction. Quantum information transmitted between codemakers cannot be copied by an eavesdropper without causing a detectable disturbance.
Inspired by an unpublished manuscript written by Steven Wiesner in April 1968, while he was participating in the Columbia University student protests [13], Charles Bennett and I realized in 1982 that quantum mechanics provides us with a channel on which passive eavesdropping is impossible. This led us and Seth Breidbart to write down what would become the leitmotif of the nascent field of quantum cryptography.

When elementary quantum systems, such as polarized photons, are used to transmit digital information, the uncertainty principle gives rise to novel cryptographic phenomena unachievable with traditional transmission media, e.g. a communications channel on which it is impossible in principle to eavesdrop without a high probability of being detected. [47]

Armed with this idea, we devised a cryptographic protocol in which a one-time pad could be safely reused indefinitely, as long as no eavesdropping is detected. This secure reuse of a one-time pad is precisely what Shannon had mathematically demonstrated to be impossible: all security is lost as soon as a “one-time” pad is used twice. Our advantage, of course, comes from the fact that we could detect eavesdropping and discontinue the use of a pad as soon as it had been compromised (yet providing perfect secrecy even on the last message that was sent), whereas he had no fundamental way to detect eavesdropping, and therefore he was forced to play safe.

In more detail, Shannon proved that the one-time pad is unconditionally secure provided the shared key is perfectly random, completely unknown of the eavesdropper, and used once only. However, even though no information leaks concerning the message in case of interception, information would leak concerning the key itself. This is of no consequence as long as the key is never reused. But if it is, the key-secrecy condition is no longer fulfilled the second time, which is why the system becomes insecure. It follows that a “one-time” pad can be reused safely, Shannon’s theorem notwithstanding, provided the previous communications have not been subject to eavesdropping, and it remains secure the first time that it is.

Expounding on these ideas, we wrote our paper on “How to re-use a one-time pad safely” in 1982 and had it published. . . a few months ago, 25 years later! [17].

The reason it took so long to publish is that as soon as it was about to be rejected from the Fifteenth Annual ACM Symposium on Theory of Computing, Bennett and I had a much better idea: we realized that it is more practical to use the quantum channel to establish a shared secret random key, and then use this key as a classical one-time pad to encode the actual message, rather than use the channel to transmit the message directly. The main advantage of this indirect approach is that even if most of the quantum information is lost in the channel—indeed, optical fibres are not very transparent to single photons over several kilometres—a random subset of a random key is still a (shorter) random key. In contrast, a small random subset of a meaningful message is fairly likely to be mostly random and totally useless.

Thus was born Quantum Key Distribution, which is now called simply QKD. We presented QKD for the first time at the 1983 IEEE International Symposium
Cryptography in a Quantum World

on Information Theory [48], but each paper was allowed only a one-page abstract. Consequently, our protocol had to wait another year before it could be published in the Proceedings of a conference held in Bengaluru, India, where I had been invited to present any paper of my choice [49]. I suspected that the idea of QKD was likely to be rejected if submitted to a conference with full published proceedings, which is why I seized the opportunity provided by a blank-cheque invitation to sneak it at that conference! This is how our original QKD protocol came to be known as “BB84”, where the Bs stand for the authors, despite the fact that we had invented and presented it in 1983. Thirty years later, Natural Computing (Springer) and Theoretical Computer Science (Elsevier) decided to join forces and publish special BB84 commemorative issues. This is how the earlier 1982 paper came to be published [47], whereas the original “BB84 paper” was published for the first time in a journal [50]. For more information on the early history of quantum cryptography, please read Ref. [51].

It was fairly easy to show that BB84 is secure against the most obvious attacks that an eavesdropper might attempt [52]. However, it took ten years after its invention before a complete formal proof of unconditional security, taking into account any attack possible according to the laws of quantum mechanics, was obtained [54]. Well, not exactly. This early proof, as well as the few that followed for the purpose of simplifying it, contained a major oversight. They proved that the key established by BB84 (and other similar QKD protocols) was perfectly secret... provided it is never used! Indeed, Renato Renner and Robert König realized ten years later that a clever adversary could keep the eavesdropped information at the quantum level (unmeasured). Later, when the key is used, say as one-time pad, the information that it leaks on the key (which would not be a problem in classical cryptography since the key would not be reused) could inform the eavesdropper about the appropriate measurement to make in order to learn more of the key and, therefore something about the message itself [55]. At first, this was only a theoretical worry, but then it was shown that the danger is real because one could purposely design a QKD scheme that could be proved secure under the old definition, but that really leaked information if the “secret” key is used [56]. Fortunately, the adequate (“composable”) definition was given and BB84 was correctly proven secure a few months later [57].

Et voilà! Quantum cryptography offers an unbreakable method for code-makers to win the battle once and for all against any possible attack available to codebreakers, short of violating the widely accepted laws of physics. Despite the discouraging news brought about by the previous sections, in which quantum mechanics appeared to be a curse for codemakers, in the end it is a blessing for the protection of privacy.

As my much missed dear friend Asher Peres once said, “The quantum taketh away and the quantum giveth back”. Indeed, quantum mechanics can be exploited to break the cryptography that is currently deployed over the worldwide Internet, via Shor’s algorithm, but quantum mechanics has also provided us with the ultimately secure solution. (To be historically exact, the quantum giveth “back” ten years before it taketh away!)
Poe was wrong. End of story!

Oh well... Not so fast. Poe was wrong in theory. Now, one has to build an apparatus that implements QKD as specified by the theoretical protocol. Exactly? Not possible! Any real implementation will be at best an approximation of the ideal protocol. The first prototype was built by Bennett and me, with the help of three students (two of whom have become highly respected researchers in the field) as early as 1989, even though the journal paper was published a few years later [52,53]. This prototype was not intended to be more than a proof of principle and some of its parts made such loud noises that we could literally hear the bits fly by... and zeroes did not make the same noise as ones. So, this first implementation was secure provided the eavesdropper is deaf!

Afterwards, serious experimental physicists entered the game and ever increasingly sophisticated devices have been built, capable of establishing secret keys over longer and longer distances. This business became so serious that companies sprung up to market QKD equipment, such as ID Quantique [55] in Switzerland. China has recently announced that it has almost completed the installation of a quantum communications network stretching two thousand kilometres from Beijing to Shanghai [59]. Several countries have plans to move the quantum highway to space, so that distances will no longer be an issue.

In the mean time, a new breed of (typically friendly) pirates has sprung up: the Quantum Hackers. In 2009, a team lead by Vadim Makarov completed a “full-field implementation of a complete attack on a running QKD connection; an installed eavesdropper obtained the entire ‘secret’ key, while none of the parameters monitored by the legitimate parties indicated a security breach” [60]. Of course, this was not an attack against BB84 or any other provably secure QKD protocol, which would have been an attack against quantum mechanics itself; this was an attack against one particular imperfect implementation of a perfect idea. The specific flaw was eradicated... and Makarov found another weakness!

And so, the game of cat and mouse between codemakers and codebreakers continues. Only the battlefield has shifted from the realm of mathematics and computer science to the realm of physics and engineering. Nevertheless, even an imperfect implementation of QKD has a significant advantage over classical systems: it must be attacked while the key establishment process is taking place. There is nothing to store for subsequent codebreaking when new technology or new algorithms become available. If the technology is available today for the implementation of some imperfect version of QKD but not yet for breaking it, everlasting security is achievable. Similarly, I have not mentioned the fact that the deployment of QKD requires the availability of an authenticated classical channel between the codemakers to avoid a person-in-the-middle attack, much as was the case for Merkle’s classical approach in 1974. However, if the codemakers can establish short-lived secure authentication keys by any method, those keys can give rise to everlasting security through the use of QKD, again an advantage that has no classical counterpart [61].

Nevertheless, it is legitimate to wonder if there is any hope of one day building an implementation of QKD so close to the ideal protocol that it will effectively be
secure against all possible attacks, regardless of the codebreaker’s technology and computing time? It is tempting to say that this would be Mission: Impossible. Surely, an army of Makarovs will spring up with increasingly clever ideas to defeat increasingly sophisticated (yet imperfect) implementations of QKD. Said otherwise, surely Poe was right in the end.

Well... Maybe not! A new approach to QKD has sprung up, based on a brilliant idea put forward by Artur Ekert as early as 1991 [62]. Instead of basing the security of QKD on the impossibility of cloning quantum information—more fundamentally the impossibility of obtaining classical information on a quantum system without disturbing it [63]—Ekert’s idea was to base the security of QKD on violations of Bell inequalities [64] in entangled nonlocal quantum systems [65]. Even though Ekert’s original 1991 QKD protocol cannot give rise to an apparatus that would be more secure than one based on BB84 [63], his fundamentally revolutionary idea opened the door to other theoretical QKD protocols that have the potential to be secure even if implemented imperfectly. The security of those so-called “device-independent QKD protocols” would depend only on the belief that information cannot travel faster than light, that the codemakers are capable of choosing their own independent randomness, and of course that they live in secure private spaces (since there is no need for codebreakers if the adversary is capable to physically eavesdrop over the codemakers’ shoulders!).

In the extreme case, highly theoretical device-independent QKD protocols have been designed whose security does not even depend on the validity of quantum mechanics itself! A recent survey of this approach is found in Ref. [66].

The catch is that the implementation of fully device-independent QKD protocols represents formidable technological challenges. It is not clear that we shall ever reach the required sophistication to turn this dream into reality. Nevertheless, a first essential step towards this goal has been achieved very recently by Ronald Hanson and collaborators in the Netherlands when they performed a long-awaited experiment in which they closed both the locality and the detection loopholes in experimental violations of Bell inequalities [67,68].

Shall we ever be able to build such a device? If so, the codemakers will have the final laugh. But what if not?

Was Poe right in the end? The jury is still out!

Acknowledgments. I am grateful to all those with whom I have had fruitful discussions on these issues in the past 36 years, starting with my lifelong collaborators Charles Bennett and Claude Crépeau. I thank Michele Mosca for allowing me to quote his “theorem”. I am also grateful to Rusins Freivalds for his invitation to present this paper to this 42nd International Conference on Current Trends in Theory and Practice of Computer Science (SOFSEM) and for his involvement in my 1998 election as Foreign Member of the Latvian Academy of Sciences. This work was supported in part by Canada’s Natural Sciences and Engineering Research Council of Canada (NSERC), the Institut transdisciplinaire d’informatique quantique (INTRIQ), the Canada Research Chair program and the Canadian Institute for Advanced Research (CIFAR).
References

1. Kahn, D.: The Codebreakers: The Comprehensive History of Secret Communication from Ancient Times to the Internet. Scribner, 2nd revised edn. (1996)
2. Singh, S.: The Code Book: The Science of Secrecy from Ancient Egypt to Quantum Cryptography. Anchor Books (2000)
3. http://tumblr.radarq.net/post/16344039232/big-brother-is-watching-you-in-the-plaza-de-george, accessed on 8 October 2015
4. Hodges, A.: Alan Turing: The Enigma. Random House (2012)
5. Rejewski, M.: How Polish mathematicians broke the Enigma cipher. Annals of the History of Computing 3(3), 213–234 (1981)
6. Tyldum, M., Moore, G.: The Imitation Game (2014)
7. https://en.wikipedia.org/wiki/W._T._Tutte, accessed on 8 October 2015
8. Tutte, W.T.: FISH and I (1998), http://www.usna.edu/Users/math/wdj/_files/documents/papers/cryptoday/tutte_fish.pdf, transcript of a lecture given at the University of Waterloo on 19 June 1998
9. QCrypt2015 (2015), http://2015.qcrypt.net, accessed on 8 October 2015
10. Poe, E.A.: A few words on secret writing. Graham’s Lady’s and Gentleman’s Magazine XIX(1), 33–38 (Jul 1841)
11. Poe, E.A.: The Gold-Bug. Philadelphia Dollar Newspaper (Jun 1843)
12. Rosenheim, S.J.: The Cryptographic Imagination: Secret Writing from Edgar Poe to the Internet. Johns Hopkins University Press (1997)
13. Shannon, C.E.: A mathematical theory of communication. Bell System Technical Journal 27(3), 379–423 (Jul 1948)
14. Shannon, C.E.: Communication theory of secrecy systems. Bell System Technical Journal 28(4), 656–715 (1949)
15. Colossus computer, https://en.wikipedia.org/wiki/Colossus_computer, accessed on 8 October 2015
16. Vernam, G.: Secret signaling system (Jul 1919), U.S. Patent 1,310,719
17. Bellovin, S.M.: Frank Miller: Inventor of the one-time pad. Cryptologia 35(3), 203–222 (2011)
18. Moscow–Washington hotline, https://en.wikipedia.org/wiki/Moscow–Washington_hotline, accessed on 8 October 2015
19. James, D.: Ché Guevara: A Biography. Rowman & Littlefield (1970)
20. Merkle, R.C.: C.S. 244 project proposal (1974), http://www.merkle.com/1974, accessed on 8 October 2015
21. Merkle, R.C.: Secure communications over insecure channels. Communications of the ACM 21(4), 294–299 (1978)
22. Diffie, W., Hellman, M.E.: New directions in cryptography. IEEE Transactions on Information Theory 22(6), 644–654 (1976)
23. Rivest, R.L., Shamir, A., Adleman, L.: A method for obtaining digital signatures and public-key cryptosystems. Communications of the ACM 21(2), 120–126 (1978)
24. Wayner, P.: British document outlines early encryption discovery (1997), http://www.nytimes.com/library/cyber/week/122497encrypt.html, accessed on 8 October 2015
25. McEliece, R.J.: A public-key cryptosystem based on algebraic coding theory. DSN Progress Report 42(44), 114–116 (1978)
26. Koblitz, N.: Elliptic curve cryptosystems. Mathematics of Computation 48(177), 203–209 (1987)
27. Miller, V.S.: Use of elliptic curves in cryptography. In: Williams, H.C. (ed.) Crypto ’85. LNCS, vol. 218, pp. 417–426. Springer (1986)
28. Feynman, R.P.: Simulating physics with computers. International Journal of Theoretical Physics 21(6/7), 467–488 (1982)
29. Feynman, R.P.: Quantum mechanical computers. Optics News 11(2), 11–20 (Feb 1985)
30. Deutsch, D.: Quantum theory, the Church-Turing principle and the universal quantum computer. Proceedings of the Royal Society of London A 400, 97–117 (1985)
31. Shor, P.W.: Polynomial-time algorithms for prime factorization and discrete logarithms on a quantum computer. SIAM Journal on Computing 26(5), 1484–1509 (1997)
32. Kitaev, A.Y.: Quantum measurements and the abelian stabilizer problem (1995), arXiv preprint quant-ph/9511026
33. Bernstein, D.J., Buchmann, J., Dahmen, E. (eds.): Post-Quantum Cryptography. Springer Science & Business Media (2009)
34. Bernstein, D.J., Lange, T.: Post-quantum cryptography, http://pqcrypto.org/, accessed on 8 October 2015
35. Micciancio, D., Regev, O.: Lattice-based cryptography, pp. 147–191 (2009). In: [33]
36. Wolchover, N.: A tricky path to quantum-safe encryption. Quanta Magazine (Sep 2015), https://www.quantamagazine.org/20150908-quantum-safe-encryption/, accessed on 8 October 2015
37. Campbell, P., Groves, M., Shepherd, D.: Soliloquy: A cautionary tale (2015), https://docbox.etsi.org/Workshop/2014/201410_CRYPTO/S07_Systems_and_Attacks/S07_Groves_Annex.pdf, accessed on 8 October 2015
38. Biasse, J.F., Song, F.: A note on the quantum attacks against schemes relying on the hardness of finding a short generator of an ideal in \( \mathbb{Q}(\zeta_p^m) \) (2015), http://cacr.uwaterloo.ca/techreports/2015/cacr2015-12.pdf, accessed on 8 October 2015
39. National Security Agency: Cryptography Today (Aug 2015), https://www.nsa.gov/ia/programs/suiteb_cryptography/, accessed on 8 October 2015
40. Grover, L.K.: Quantum mechanics helps in searching for a needle in a haystack. Physical Review Letters 79(2), 325–328 (1997)
41. Bennett, C.H., Bernstein, E., Brassard, G., Vazirani, U.: Strengths and weaknesses of quantum computing. SIAM Journal on Computing 26(5), 1510–1523 (1997)
42. Brassard, G., Salvail, L.: Quantum Merkle puzzles. In: Second International Conference on Quantum, Nano and Micro Technologies. pp. 76–79 (2008)
43. Brassard, G., Heyer, P., Kalach, K., Kaplan, M., Laplante, S., Salvail, L.: Merkle puzzles in a quantum world. In: Rogaway, P. (ed.) Crypto 2011. LNCS, vol. 6841, pp. 391–410. Springer (2011)
44. Boyer, M., Brassard, G., Heyer, P., Tapp, A.: Tight bounds on quantum searching. Fortschritte der Physik 46(4&5), 493–505 (1998)
45. Wootters, W.K., Zurek, W.H.: A single quantum cannot be cloned. Nature 299(5886), 802–803 (1982)
46. Wiesner, S.: Conjugate coding. ACM Sigact News 15(1), 78–88 (1983), original manuscript written in 1968
47. Bennett, C.H., Brassard, G., Breidbart, S.: Quantum cryptography II: How to re-use a one-time pad safely even if P=NP. Natural Computing 13(4), 453–458 (2014), original manuscript written in 1982
48. Bennett, C.H., Brassard, G.: Quantum cryptography and its application to provably secure key expansion, public-key distribution, and coin-tossing. In: Proceedings of IEEE International Symposium on Information Theory. p. 91 (Sep 1983)
49. Bennett, C.H., Brassard, G.: Quantum cryptography: Public key distribution and coin tossing. In: Proceedings of International Conference on Computers, Systems and Signal Processing, pp. 175–179 (Dec 1984)

50. Bennett, C.H., Brassard, G.: Quantum cryptography: Public key distribution and coin tossing. Theoretical Computer Science 560, Part 1, 7–11 (2014)

51. Brassard, G.: Brief history of quantum cryptography: A personal perspective. In: Proceedings of IEEE Information Theory Workshop on Theory and Practice in Information Theoretic Security. pp. 19–23 (Oct 2005), http://arxiv.org/abs/quant-ph/0604072

52. Bennett, C.H., Bessette, F., Brassard, G., Salvail, L., Smolin, J.: Experimental quantum cryptography. Journal of Cryptology 5(1), 3–28 (1992)

53. Bennett, C.H., Brassard, G., Ekert, A.K.: Quantum cryptography. Scientific American 267(4), 50–57 (Oct 1992)

54. Mayers, D.: On the security of the quantum oblivious transfer and key distribution protocols. In: Coppersmith, D. (ed.) Crypto 1995. LNCS, vol. 963, pp. 124–135. Springer (1995)

55. Renner, R., König, R.: Universally composable privacy amplification against quantum adversaries. In: Kilian, J. (ed.) TCC 2005. LNCS, vol. 3378, pp. 407–425. Springer (Feb 2005)

56. König, R., Renner, R., Bariska, A., Maurer, U.: Small accessible quantum information does not imply security. Physical Review Letters 98(14), 140502 (2007)

57. Renner, R., Gisin, N., Kraus, B.: Information-theoretic security proof for quantum-key-distribution protocols. Physical Review A 72(1), 012332 (2005)

58. ID Quantique, http://www.idquantique.com

59. Fadilpašić, S.: China's quantum communications network almost ready (Aug 2015), http://www.itproportal.com/2015/08/31/chinas-quantum-communications-network-almost-ready/ accessed on 9 October 2015

60. Gerhardt, I., Liu, Q., Lamas-Linares, A., Skaar, J., Kurtsiefer, C., Makarov, V.: Full-field implementation of a perfect eavesdropper on a quantum cryptography system. Nature Communications 2, 349 (2011)

61. Unruh, D.: Everlasting quantum security. IACR Cryptology ePrint Archive 2012, 177 (2012), http://www.researchgate.net/publication/268011502

62. Ekert, A.K.: Quantum cryptography based on Bell’s theorem. Physical Review Letters 67(6), 661–663 (1991)

63. Bennett, C.H., Brassard, G., Mermin, N.D.: Quantum cryptography without Bell’s theorem. Physical Review Letters 68(5), 557–559 (1992)

64. Bell, J.S.: On the Einstein-Podolsky-Rosen paradox. Physics 1(3), 195–200 (1964)

65. Einstein, A., Podolsky, B., Rosen, N.: Can quantum-mechanical description of physical reality be considered complete? Physical Review 47(10), 777–780 (1935)

66. Ekert, A., Renner, R.: The ultimate physical limits of privacy. Nature 507(7493), 443–447 (2014)

67. Hensen, B., Bernien, H., Dréau, A., Reiserer, A., Kalb, N., Blok, M., Ruitenberg, J., Vermeulen, R., Schouten, R., Abellán, C., Amaya, W., Pruneri, V., Mitchell, M., Markham, M., Twitchen, D., Elkouss, D., Wehner, S., Taminiau, T., Hanson, R.: Experimental loophole-free violation of a Bell inequality using entangled electron spins separated by 1.3 km (2015), arXiv preprint arXiv:1508.05949

68. Johnston, H.: Physicists claim ‘loophole-free’ Bell-violation experiment. Physics World (Sep 2015), http://physicsworld.com/cws/article/news/2015/sep/02/physicists-claim-loophole-free-bell-violation-experiment