

Applications in Security

The question of many people’s minds is whether and when “quantum computers would kill RSA”? We will review some recent work in security applications:

- generating random strings
- quantum key distribution
- Shor factoring
- Grover-based factoring
- variational factoring.

While the first two happily live in “vendor-land”, the latter three are more involved.

1. Generating random strings

US authorities now recommend using random strings only from quantum effects, rather than pseudo-random generators. In some cases Bierhorst et al. [2018], quantum random number generators (RNG) come with strong guarantees, but often, it seems an overkill to utilize a quantum computer to generate random numbers. There are now purpose-built devices Avesani et al. [2018] that can generate random strings at 17 Gbps, exceeding what can be done with near-term quantum computers. The purpose-built devices can be bought, e.g., from ID Quantique.

2. Quantum key distribution

An important quantum technology in security is quantum key distribution, which makes it possible to certify that the communication has not been intercepted. There are two approaches:

- *Prepare-and-measure*: measuring an unknown quantum state changes it.
- *Entanglement-based*: measuring one of two entangled quantum systems affects the other.

Either way, one can calculate the amount of information that has been intercepted by measurement. ID Quantiq showcased quantum key distribution at 307 km, and sells related devices. Toshiba demonstrated QKD at 100 km of fiber in 2004 and the first with a continuous key rate exceeding 10 Mbit/second in 2017. CTU has purchased such devices from both ID Quantiq and Toshiba.

3. Factoring integers

Much of modern cryptoprimitives are built on factoring of large integers. A textbook version of public-key cryptography, here cited from Nielsen and Chuang [2002] in verbatim, is as follows:

- (1) Select two large prime numbers, p and q .
- (2) Compute the product $n = pq$.
- (3) Select at random a small odd integer, e , that is relatively prime to $\phi(n) = (p - 1)(q - 1)$.
- (4) Compute d , the multiplicative inverse of e , modulo $\phi(n)$.
- (5) The RSA public key is the pair $P = (e, n)$. The RSA secret key is the pair $S = (d, n)$.

The encryption of message M on $\log n$ bits involves $M^e \pmod n$ to obtain $E(M)$, while decryption requires $E(M)^d \pmod n$.

What is the complexity of factoring n to p and q ?

- $\text{poly}(\log(n))$ is the runtime of factoring algorithms on a BSS machine. Testing whether an integer is a prime is in P, but does not provide the factors, when the number is not prime.
- $O(n^{1/4})$ is the runtime of the best deterministic factoring algorithms for factoring an integer n with $\log n$ bits in length.
- $O(\exp(c(\log n)^{1/3}(\log \log n)^{2/3}))$ is the runtime of the best randomized algorithms, for some constant c and integer n . The runtime is thus subexponential, but not polynomial time: $O(\exp(\sqrt{(\log n)(\log \log n)}) = O(n)$. It is thus unlikely that factoring is NP-Complete. The elliptic curve method (ECM, Lenstra Jr [1987]) is the fastest known algorithm for small numbers, e.g. within 100 digits. The the number field sieve (NFS, Lenstra et al. [1990]) is the best classical algorithm for large numbers, and has been used to factor a 240-digit (795-bit) number in 900 core-years.
- $O((\log n)^2(\log \log n)(\log \log \log n))$ is the runtime of a quantum algorithm introduced by Peter Shor [1994], along with a polynomial-time (in $\log n$) classical post-processing algorithm.

3.1. Shor factoring. Peter Shor introduced an algorithm for factoring integers Shor [1994], which based on two facts of number theory, makes it possible to reduce factoring to order finding, i.e., determining r in $f(x+r) = f(x)$ for $f(x) = a^x$. When one receives a composite number n , it uses $O(\log^3 n)$ order-finding operations to produce a non-trivial factor of n with a constant probability.

This is based on the following facts:

Theorem 5.2 in Nielsen and Chuang [2002]: Suppose that n is an L -bit composite number, and x is a non-trivial solution to the equation $x^2 = 1 \pmod n$ in the range $1 \leq x \leq n$, i.e., neither $x = 1 \pmod n$ nor $x = n - 1 = -1 \pmod n$. Then at least $\gcd(x-1, n)$ and $\gcd(x+1, n)$ is a non-trivial factor of n can be computed using $O(L^3)$ operations.

Theorem 5.3 in Nielsen and Chuang [2002]: Suppose that $n = p_1^{\alpha_1} p_2^{\alpha_2} \dots p_m^{\alpha_m}$ is the prime factorization of an odd composite positive integer. Let x be an integer chosen uniformly at random, subject to the requirements that $1 \leq x \leq n-1$ and x is co-prime to n . Let r be the order of $x \pmod n$. Then the probability r is even and $x^{r/2} \neq -1 \pmod n$ is greater or equal to $1 - \frac{1}{2^m}$.

With these facts, we can formulate the Shor factoring algorithm:

- (1) If n is even, return 2.
- (2) If $n = a^b$ for $a \geq 1$ and $b \geq 2$, return a .
- (3) Choose x in $[1, n-1]$. If $\gcd(x, n) > 1$, return $\gcd(x, n)$.
- (4) Use order-finding to find the order r of x modulo n . If r is even and $x^{r/2} \neq -1 \pmod n$ and either of $\gcd(x^{r/2} - 1, n)$ and $\gcd(x^{r/2} + 1, n)$ is non-trivial, return the non-trivial factor.
- (5) Repeat from 3 otherwise.

Shor's order-finding works as follows:

- (1) creates an initial, Q -qubit state $|0\rangle^{\otimes Q}$
- (2) apply Hadamard transform on it: $\frac{1}{\sqrt{Q}} \sum_{k=0}^{Q-1} |k\rangle$
- (3) apply the function $f(x) = a^x \pmod N$ using $U_f|x, 0^n\rangle = |x, f(x)\rangle$ to obtain

$$U_f \frac{1}{\sqrt{Q}} \sum_{x=0}^{Q-1} |x, 0^n\rangle = \frac{1}{\sqrt{Q}} \sum_{x=0}^{Q-1} |x, f(x)\rangle$$

such that the value we are looking for is in the phase

- (4) apply the quantum Fourier transform: $\frac{1}{Q} \sum_{x=0}^{Q-1} \sum_{y=0}^{Q-1} \omega^{xy} |y, f(x)\rangle$
- (5) obtain y by measuring the first register. The probability of measuring $|y, z\rangle$ is

$$\frac{1}{Q^2} \frac{\sin^2(\frac{\pi m r y}{Q})}{\sin^2(\frac{\pi r y}{Q})}$$

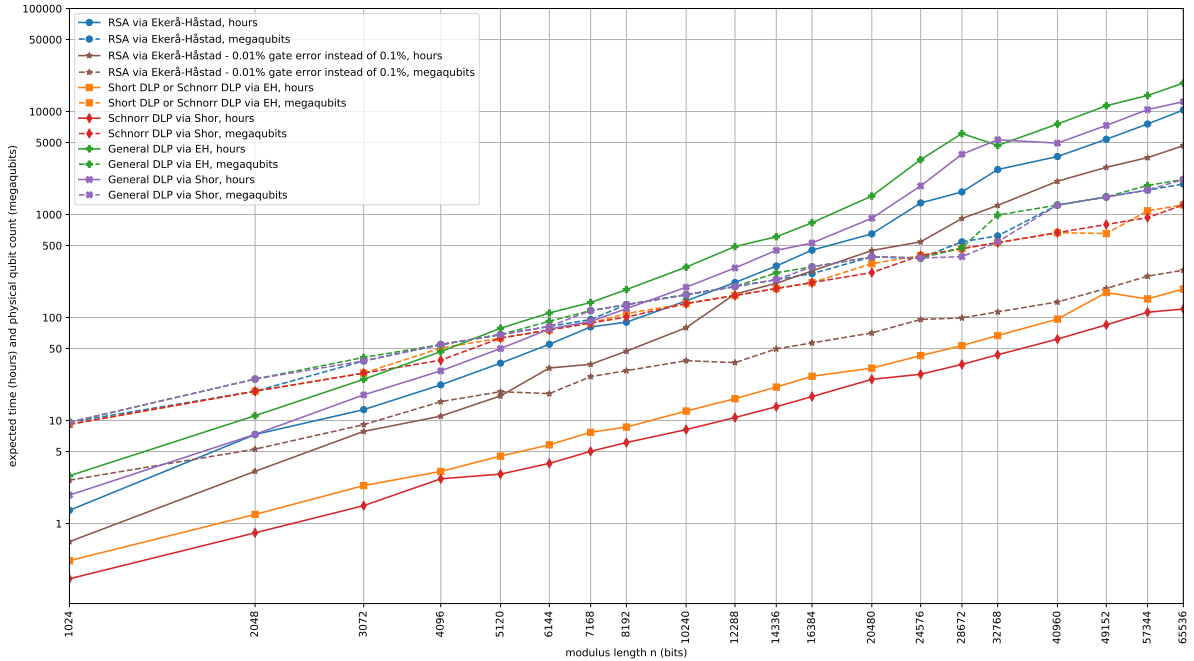


FIGURE 10.1. Scaling of Shor's Factoring: Log-log plot of estimated space (in the millions of qubits) and expected-time costs (days required) with the number of bits of RSA keys, cited from Gidney and Ekerå [2021] in verbatim.

Let us consider the example of $n = 15$.

- (1) Let us consider $n = 15$ and a random number x coprime (having no non-trivial common factors) with n , e.g., $x = 7$.
- (2) Compute the order r of x modulo n , as follows: apply Hadamard transform to the first register of $|0\rangle|0\rangle$. Compute $f(k) = x^k \bmod n$ in the second register

$$\frac{1}{\sqrt{2^t}}[|0\rangle|1\rangle + |1\rangle|7\rangle + |2\rangle|4\rangle + |3\rangle|13\rangle + |4\rangle|1\rangle + |5\rangle|7\rangle + |6\rangle|4\rangle + \dots]$$

When inverse Fourier transform is applied to the first register (seen as $2^t = 2048$ frequencies) and the second register is measured, one obtains one of 1, 7, 4, or 13. Eventually, we obtain $r = 4$ as the order of $x = 7$.

- (3) Classically, we see r is even, and $x^{r/2} \bmod n = 7^2 \bmod 15 = 4 \neq -1 \bmod 15$. Again classically, we run $\gcd(x^2 - 1, 15) = 3$ and $\gcd(x^2 + 1, 15) = 5$ to obtain two factors.

Shor's factoring has been demonstrated for the number of 15 more than two decades ago, and the scalability beyond is still very much a subject of lively discussion. A Google team Gidney and Ekerå [2021] estimates that one could perform factoring of 2048-bit RSA integers in 8 hours using 20 million noisy qubits. (See Figure 10.1.) The assumptions of a planar grid of qubits with nearest-neighbor connectivity, physical gate error rate of 10^{-3} , a surface code cycle time of 1 microsecond, and the use of surface codes are all quite realistic. Surface codes are textbook material [Nielsen and Chuang, 2002, Chapter 10], although not covered by this course. A French team Gouzien and Sangouard [2021] suggested that one could perform factoring of 2048-bit RSA integers in 177 days with 13436 qubits, without being very explicit about the requirement of 430 million memory qubits. Likewise, the use of 3D gauge color codes is out of reach in current qubit technologies. Otherwise, the assumptions of physical gate error rate of 10^{-3} , a processor cycle time of 1 microsecond are quite realistic.

3.2. Grover-based factoring. Bernstein et al. [2017] introduced another quantum algorithm for factoring, which they call GEECM (Grover plus Edwards Elliptic Curve Method). To gain some intuition, consider the trial division, where we would generate a small primes and perform Grover search for those

that divide the n . It reduces the number of operations of Edwards Elliptic Curve Method from $L^{\sqrt{2}+o(1)}$ to $L^{1+o(1)}$ for $L = \exp(\sqrt{\log \sqrt{n} \log \log \sqrt{n}})$.

3.3. Variational factoring. In principle, you can use drastically fewer qubits in some cases, but with lesser hopes of speed-up. Notably, the explicit, “schoolbook” binary multiplication of p and q yields equations that have to be satisfied by bits p_i and q_i and carry bits $z_{i,j}$. One can formulate a “least-squares version” of the problem, which would minimise the sum of residuals squared, across the equations (bits). Clearly, this would be a QUBO, as in the previous lecture, and approached with, e.g., QAOA without any guarantees of finding the solution. On the flipside, one can get lucky. For instance, Karamlou et al. [2021] report factoring 1099551473989, 3127, and 6557 with 3, 4, and 5 qubits, respectively, using a QAOA.

In a very similar spirit, a Chinese team Yan et al. [2022] got to the frontpages of many newspapers announcing that 2048-bit semi-prime number can be factored on a NISQ level computer with 372 physical qubits and a gate depth in the thousands. The same paper has shown that a 48-bit number can be factored using the Schnorr factoring and QAOA. Unfortunately, they did not analyze how many runs of the circuit this would require in general. Our analyses Kungurtsev et al. [2022] show would scale much worse than the runtime of the Shor factoring.

3.4. A Rejoinder. In the US, Congress passed Quantum Computing Cybersecurity Preparedness Act¹ in December 2022, which bars federal authorities from using cryptoprimitives based on factoring. It is unlikely that this is based on the discovery of a new factoring algorithm, but rather based on the risk of there being one. In many information security standards, you need to be sure that if you encrypt today, no one will be able to decrypt without knowing the key for the next 20+ years. In “Store Now, Decrypt Later” attacks, nation states already gain access to large troves of encrypted information, in the hope that they would be able to decrypt it in the near future. Notice that for digital signatures (e.g., certificates on the web), the risk is much less: you can wait until a new factoring algorithm appears.

¹<https://www.congress.gov/bill/117th-congress/house-bill/7535/text>

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