TAURUS

Quantum Computing Risk & Post-Quantum Crypto Standards

JP Aumasson

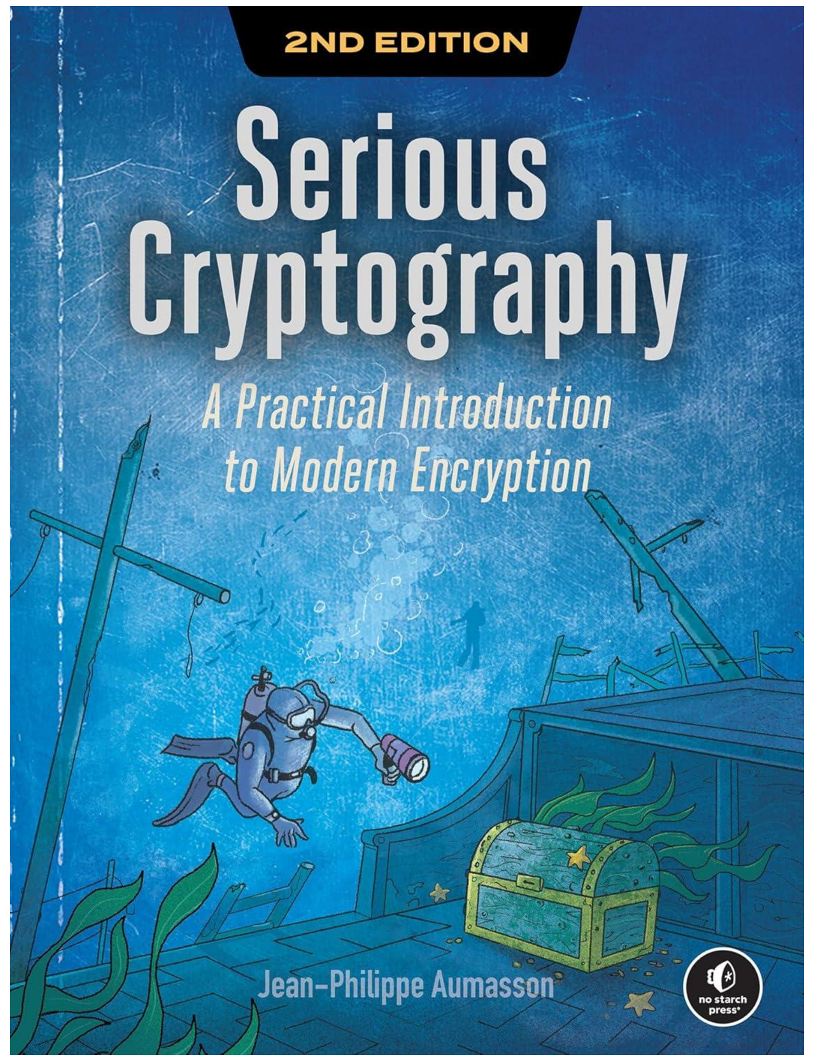
https://aumasson.jp

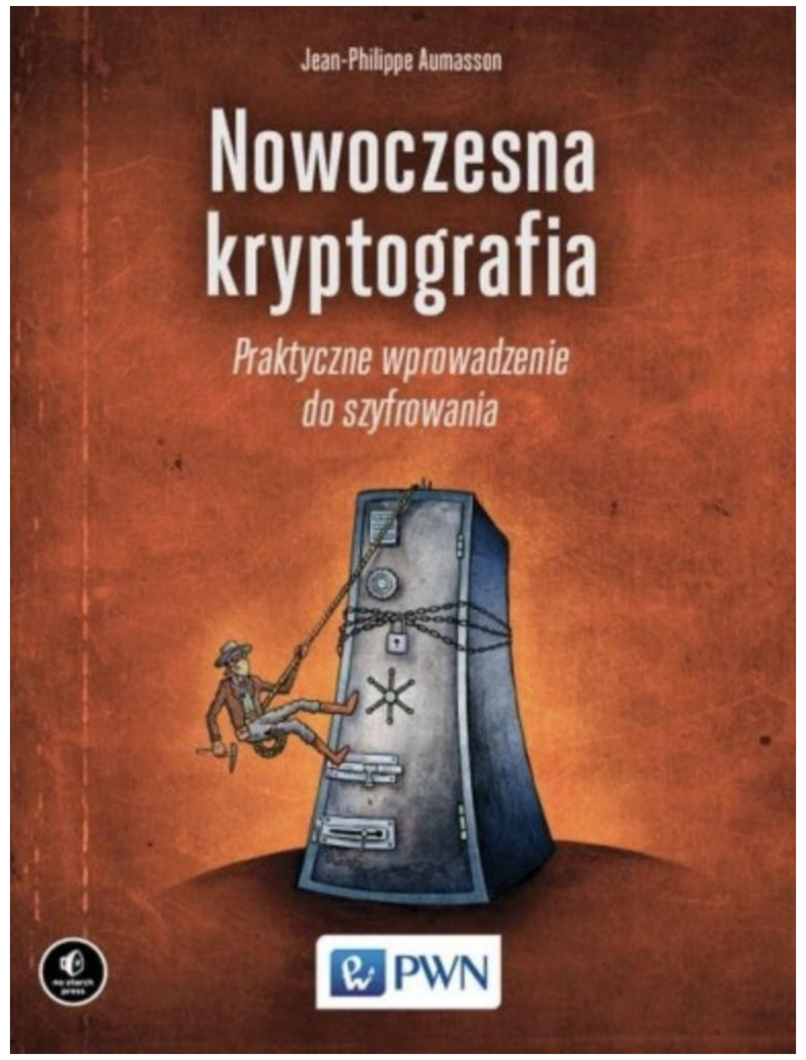
Background

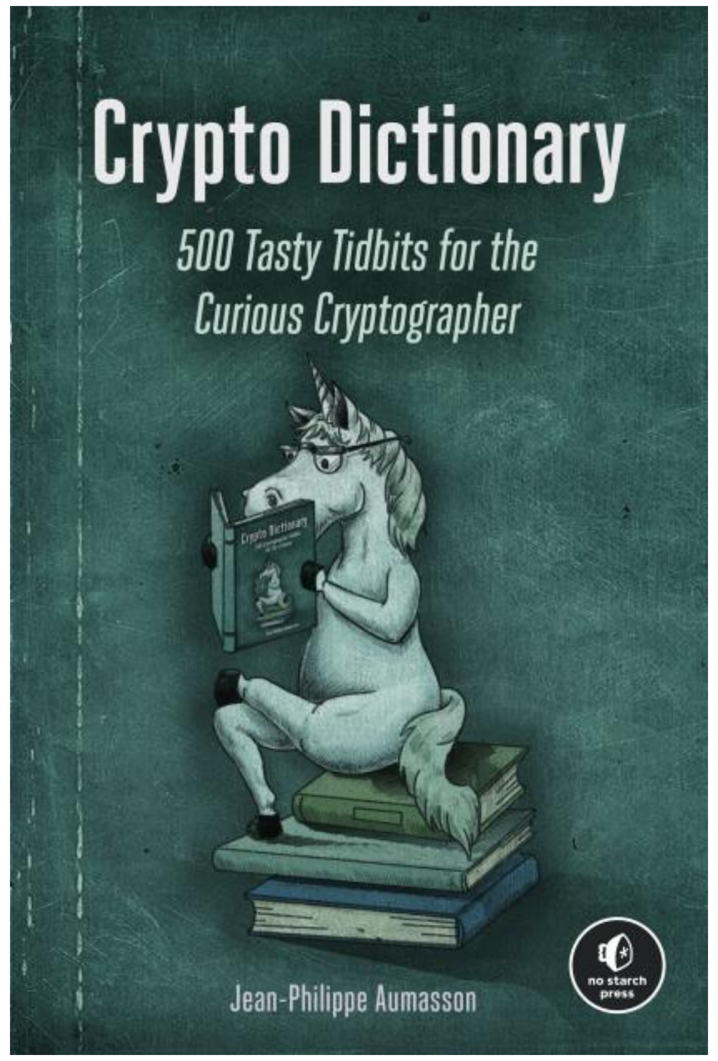
Co-founder & chief security officer of **Taurus SA**

- Swiss regulated firm founded in 2018, team of 90+
- **Digital asset custody** tech and infrastructure
- Cool tech: HSM, MPC, k8s, etc.

https://taurushq.com   https://t-dx.com







- 20 years in cryptography & security
- BLAKE2, BLAKE3, SipHash, etc.
- Crypto*graphy* books

https://aumasson.jp

Simulating Physics with Computers

Richard P. Feynman

Department of Physics, California Institute of Technology, Pasadena, California 91107

Received May 7, 1981

Not to break crypto..

5. CAN QUANTUM SYSTEMS BE PROBABILISTICALLY SIMULATED BY A CLASSICAL COMPUTER?

Now the next question that I would like to bring up is, of course, the interesting one, i.e., Can a quantum system be probabilistically simulated by a classical (probabilistic, I'd assume) universal computer? In other words, a computer which will give the same probabilities as the quantum system does. If you take the computer to be the classical kind I've described so far, (not the quantum kind described in the last section) and there're no changes in any laws, and there's no hocus-pocus, the answer is certainly, No! This is called the hidden-variable problem: it is impossible to represent the results of quantum mechanics with a classical universal device. To learn a little bit about it, I say let us try to put the quantum equations in a form as close as

… but simulate quantum physics

4. QUANTUM COMPUTERS—UNIVERSAL QUANTUM SIMULATORS

The first branch, one you might call a side-remark, is, Can you do it with a new kind of computer—a quantum computer? (I'll come back to the other branch in a moment.) Now it turns out, as far as I can tell, that you can simulate this with a quantum system, with quantum computer elements. It's not a Turing machine, but a machine of a different kind. If we disregard the continuity of space and make it discrete, and so on, as an approximation (the same way as we allowed ourselves in the classical case), it does seem to

Quantum bits (qubits)

Superposition state $\alpha\ |0\rangle + \beta\ |1\rangle$

0 with probability $|\ \alpha\ |^2$

Observation, random outcome

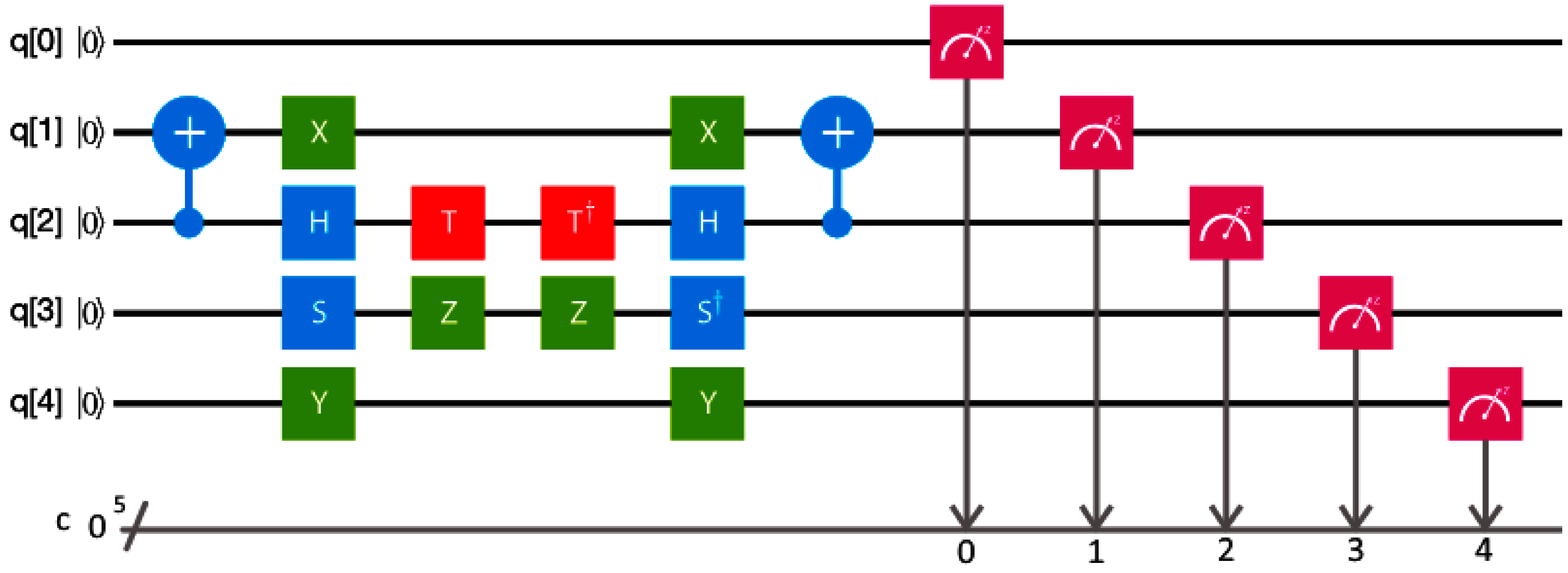
1 with probability $|\ \beta\ |^2$

α, β are"probabilities" called ***amplitudes***
(can be complex, and negative numbers)

Once observed, a qubit stays 0 or 1 forever

Quantum algorithms

Circuits of quantum gates, transforming a quantum state, ending with an observation



Can be simulated with basic linear algebra but does no scale, exponential cost:

- **Quantum state** = vector of 2^N amplitudes for N qubits
- **Quantum gates** = matrix multiplications, with $O(2^{3N})$ complexity

Quantum speedup

When quantum computers can solve a problem faster than classical computers

Most interesting: **Superpolynomial** quantum speedup (“exponential" boost)

List of problems on the **Quantum Zoo**: http://math.nist.gov/quantum/zoo/

Quantum parallelism

Quantum computers “work" on all values simultaneously, via **superposition**

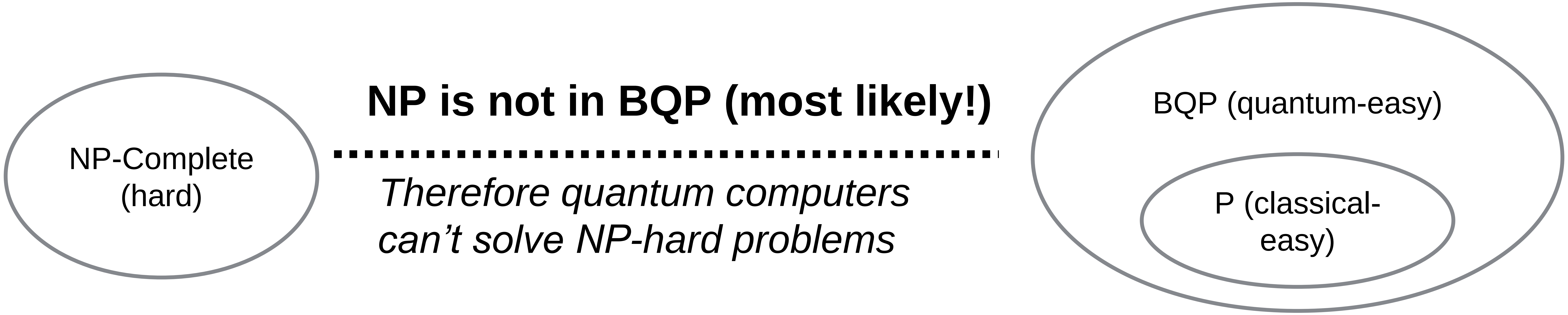
But they do not *“try every answer in parallel and pick the best”*

You can only **observe one “value”** that results from the interference of all,
as a projection from the Hilbert space where qubits “live" to some basis

NP-complete problems

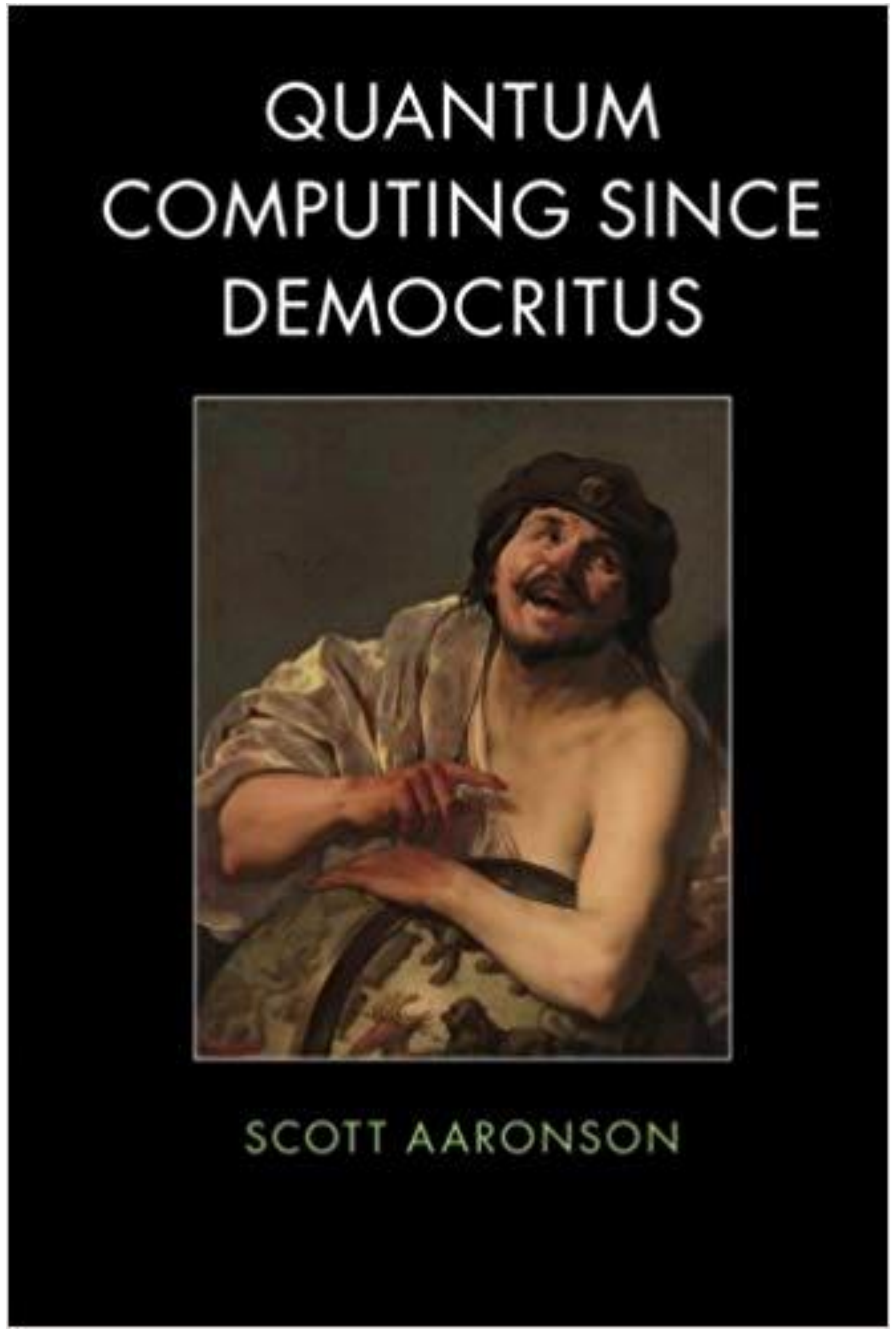
- Solution hard to find, but easy to verify
- Includes constraint satisfaction problems (SAT, TSP, knapsacks, etc.)
- Sometimes leveraged in crypto (lattice problems in post-quantum schemes)

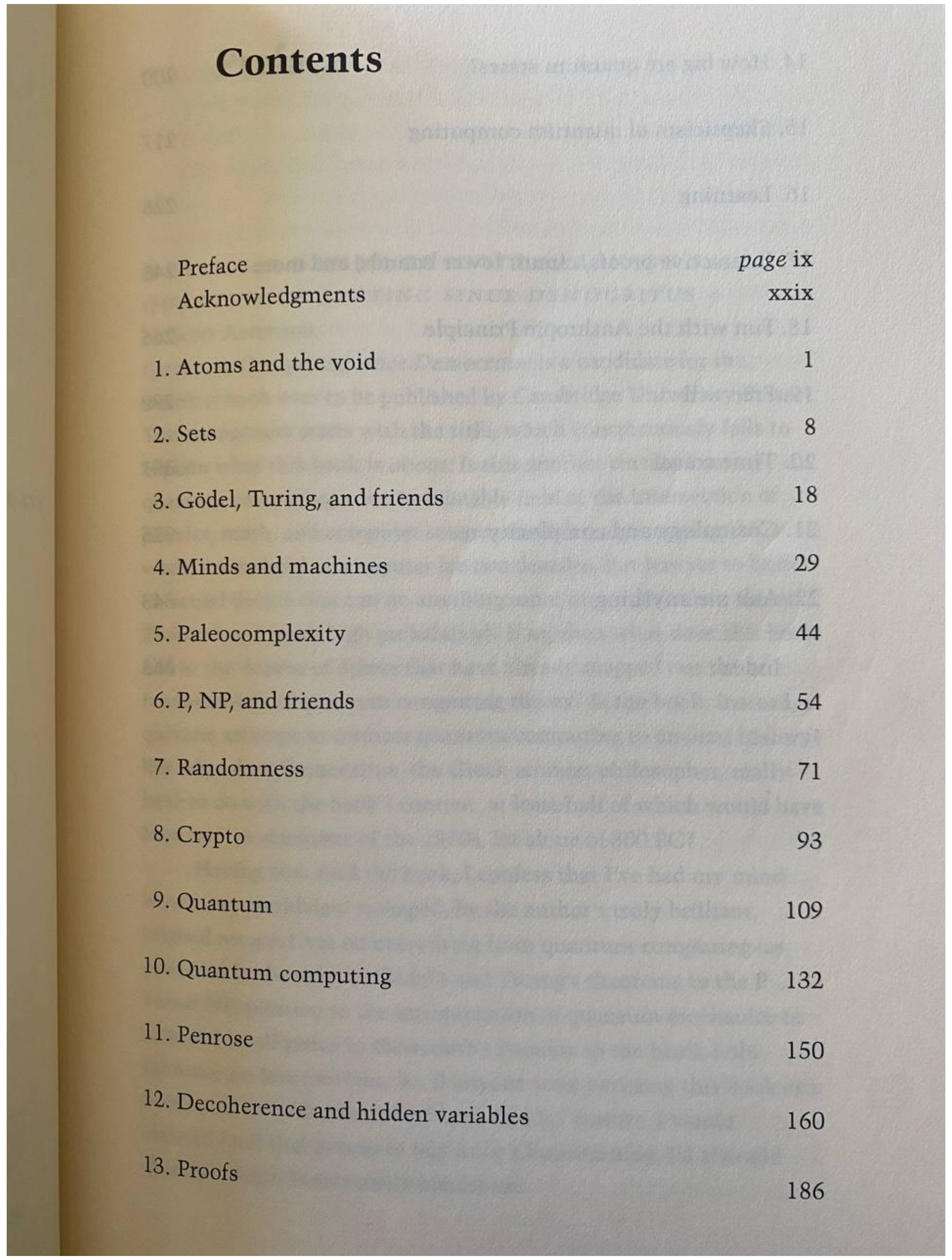
CanNOT be solved faster with quantum computers!



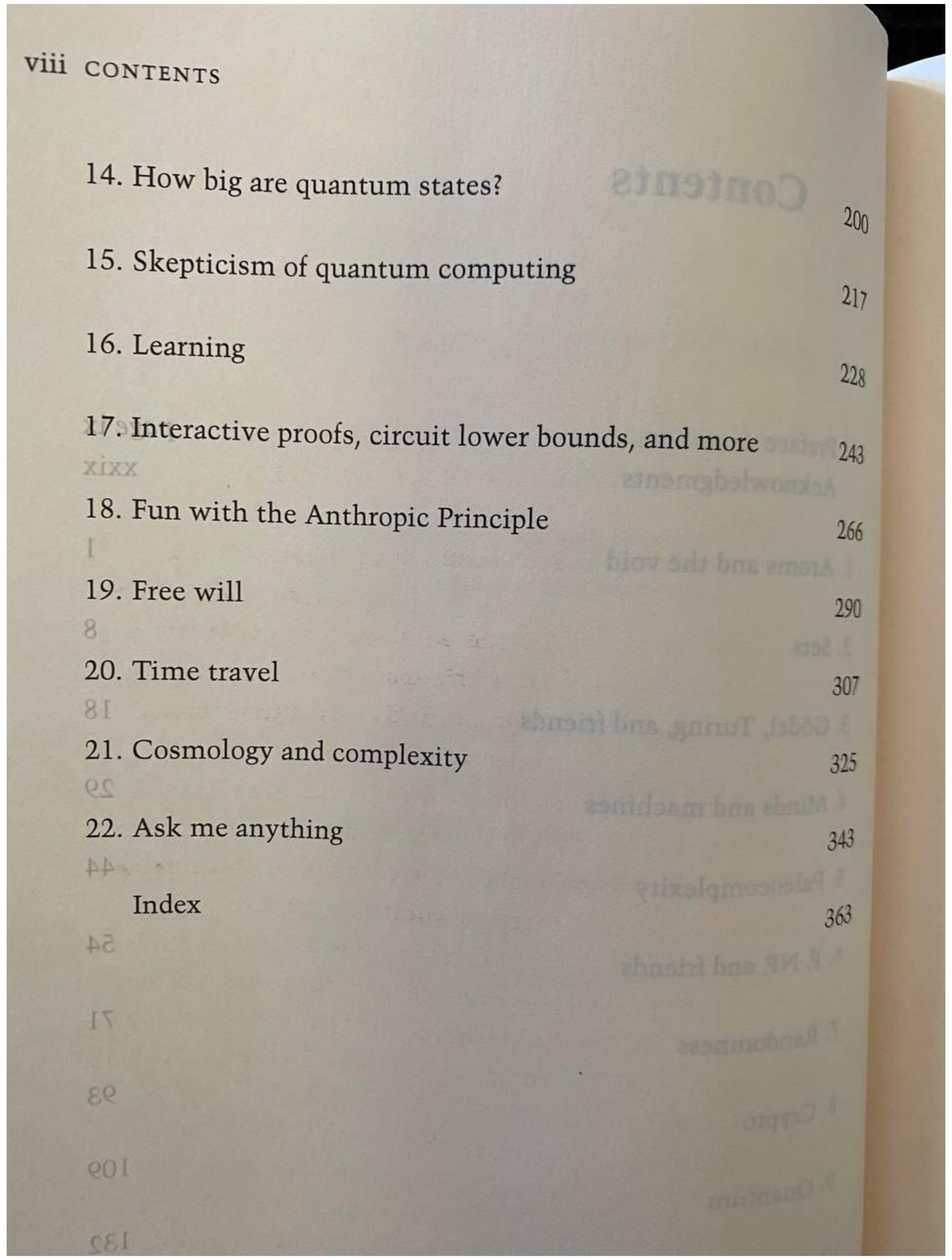
BQP = bounded-error quantum polynomial time, what QC can solve efficiently

Recommended reading

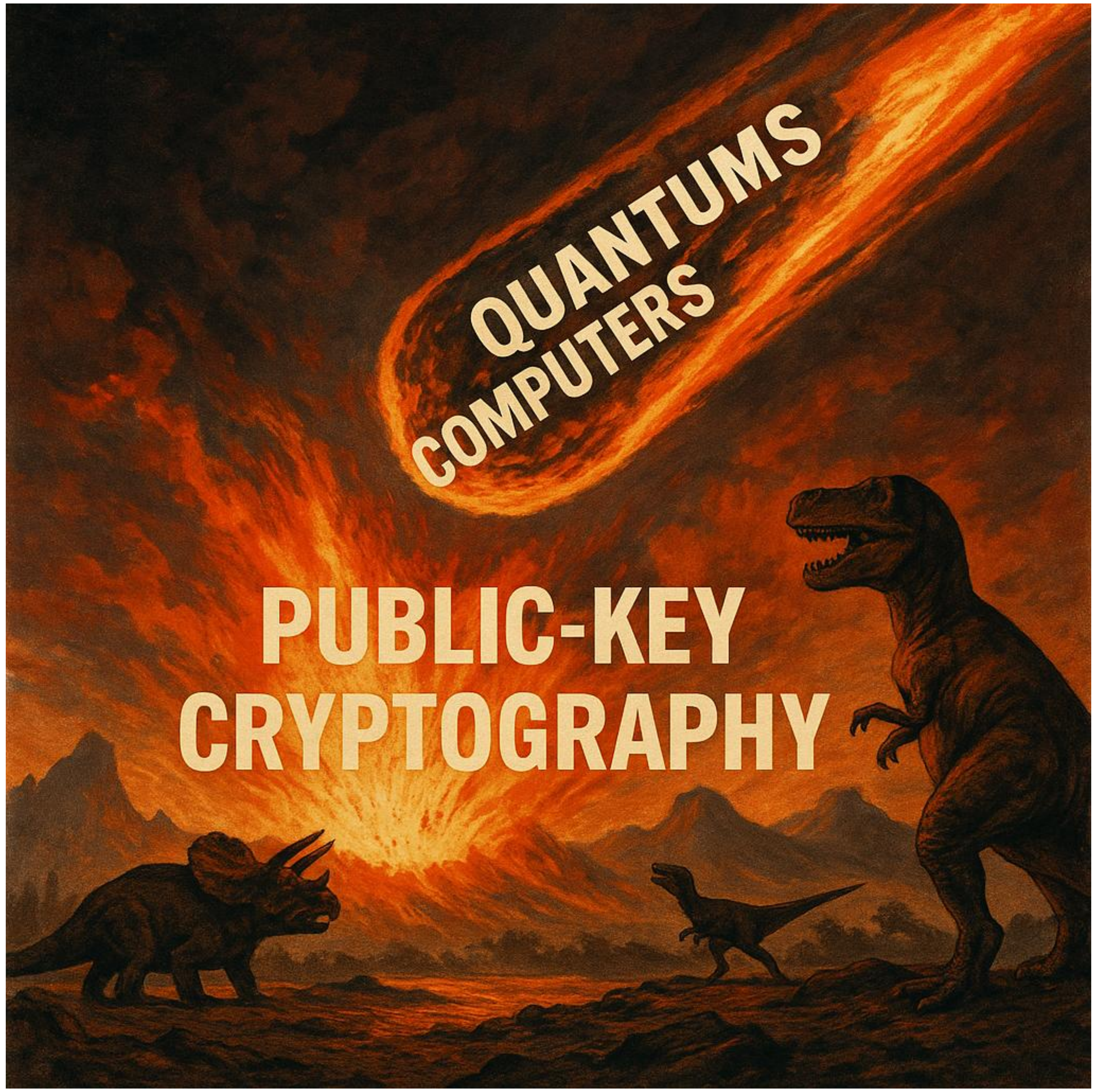




Contents



Impact on cryptography



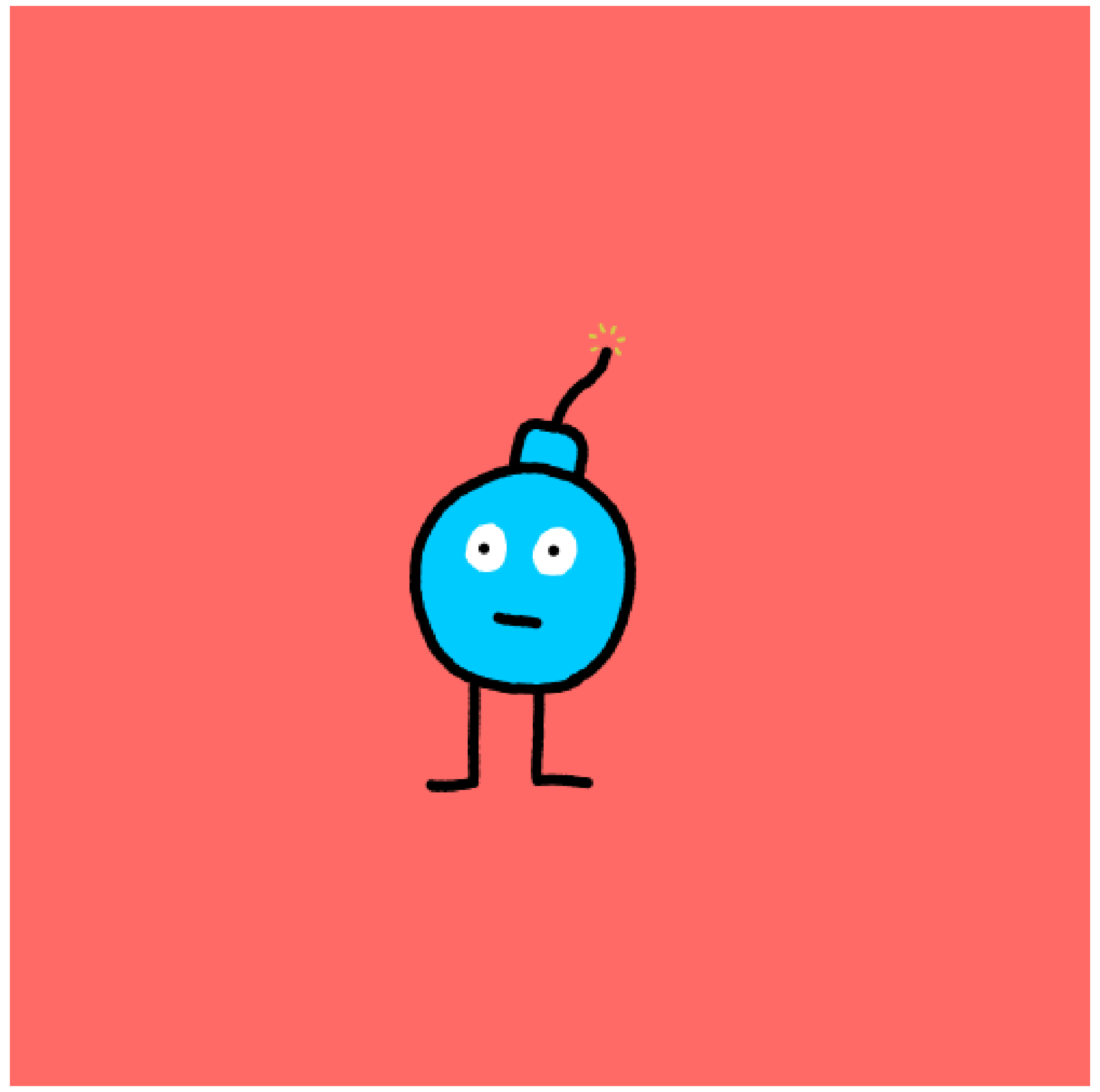
Shor’s quantum algorithm

Polynomial-time algorithm for the following problems:

- Computes **p** given **n** = **pq** → RSA dead
- Computes **d** given **y** = $\mathbf{x}^{\mathbf{d}}$ mod **p** → ECC/DH dead

Practically impossible on a classical machine

#QuantumSpeedup



How bad for crypto?

Worse

Mild: <u>Signatures</u> (ECDSA, Ed25519, etc.)
Broken sigs can be reissued with a post-quantum algorithm
Applications: PKI certificates, code signing, blockchains

Bad: <u>Key agreement</u> (Diffie-Hellman, ECDH, etc.)
Partially mitigated by secret internal states and reseeding
Applications: TLS, end-to-end messaging

Terrible: <u>Encryption</u> (RSA encryption, ECIES, etc.)
Encrypted messages compromised forever
Applications: Key encapsulation, secure enclaves

Not there yet

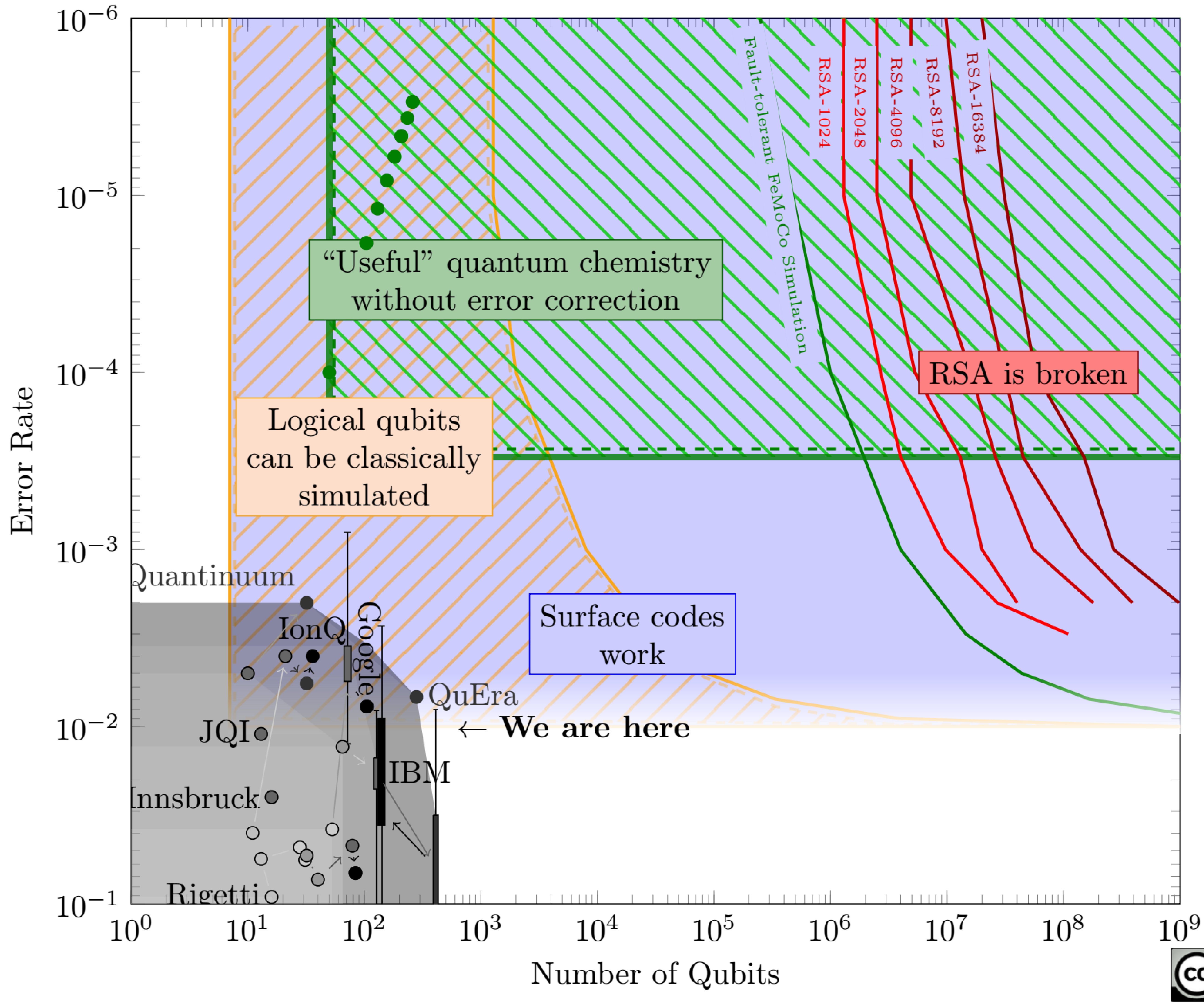
Millions of qubits to break RSA, to implement **error correction**

QC in its infancy, only research prototypes useless in practice

Google and IBM leading

2 main dimensions:

- Error rate
- Qubits number (physical, logical)



https://sam-jaques.appspot.com/quantum_landscape_2024

Beware PR BS

Speculative, exaggerated, misleading claims from QC companies, amplified in clickbait media

JD Supra

Quantum Leap: Google Claims Its New Quantum Computer Provides Evidence That We Live in a Multiverse

Google's latest refinement to its quantum computer, Willow, may represent such a moment. By achieving computational feats once thought to be confined to...

8 Jan 2025

PCMag

Google's Quantum Chip Can Do in 5 Minutes What Would Take Other Computers 10 Septillion Years

Google's quantum computing division unveiled a new chip, dubbed Willow, that the tech giant says makes it infinitely faster and better than existing...

10 Dec 2024

Google's Quantum Chip Can Do in 5 Minutes What Would Take Other Computers 10 Septillion Years

Google makes a quantum leap that suggests we may live in a multiverse.

By Kate Irwin Dec 10, 2024

Harnessing a new type of material

All of today's announcements build on our team's recent breakthrough: the world's first topoconductor. This revolutionary class of materials enables us to create *topological superconductivity*, a new state of matter that previously existed only in theory. The advance stems from Microsoft's innovations in the design and fabrication of gate-defined devices that combine indium arsenide (a semiconductor) and aluminum (a superconductor). When cooled to near absolute zero and tuned with magnetic fields,

Quantum supremacy?

Google thinks it's close to "quantum supremacy." Here's what that really means.

It's not the number of qubits; it's what you do with them that counts.

by Martin Giles and Will Knight   March 9, 2018

Seventy-two may not be a large number, but in quantum computing terms, it's massive. This week Google unveiled Bristlecone, a new quantum computing chip with 72 quantum bits, or qubits—the fundamental units of computation

When it Looks too Good to be True..

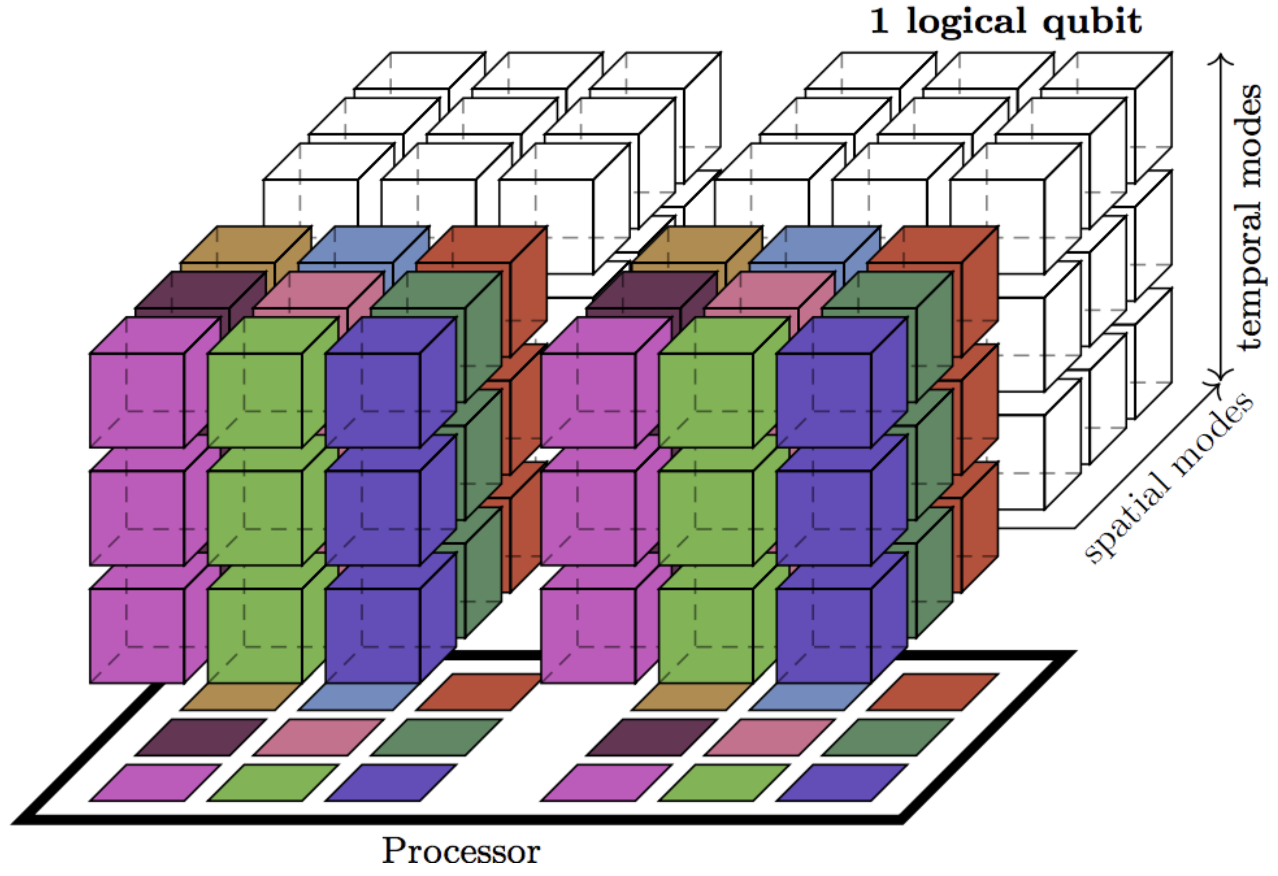
Factoring 2 048 RSA integers in 177 days with 13 436 qubits and a multimode memory

Élie Gouzien* and Nicolas Sangouard†
Université Paris–Saclay, CEA, CNRS, Institut de physique théorique, 91 191 Gif-sur-Yvette, France
(Dated: March 11, 2021)

We analyze the performance of a quantum computer architecture combining a small processor and a storage unit. By focusing on integer factorization, we show a reduction by several orders of magnitude of the number of processing qubits compared to a standard architecture using a planar grid of qubits with nearest-neighbor connectivity. This is achieved by taking benefit of a temporally and spatially multiplexed memory to store the qubit states between processing steps. Concretely, for a characteristic physical gate error rate of 10^{-3}, a processor cycle time of 1 microsecond, factoring a 2 048 bits RSA integer is shown possible in 177 days with a processor made with 13 436 physical qubits and a multimode memory with 2 hours storage time. By inserting additional error-correction steps, storage times of 1 second are shown to be sufficient at the cost of increasing the runtime by about 23 %. Shorter runtimes (and storage times) are achievable by increasing the number of qubits in the processing unit. We suggest realizing such an architecture using a microwave interface between a processor made with superconducting qubits and a multiplexed memory using the principle of photon echo in solids doped with rare-earth ions.

Introduction — Superconducting qubits form the building blocks of one of the most advanced platforms for realizing quantum computers [1]. The standard architecture consists in laying superconducting qubits in a 2D grid and making the computation using only neighboring interactions. Recent estimations showed however that fault-tolerant realizations of various quantum algorithms with this architecture would require millions physical qubits [2–4]. These performance analyses naturally raise the question of an architecture better exploiting the potential of superconducting qubits.

In developing a quantum computer architecture we



Sam Jaques @sejaques

Replying to @veorq

Very important caveat: it needs 430 million "memory qubits"

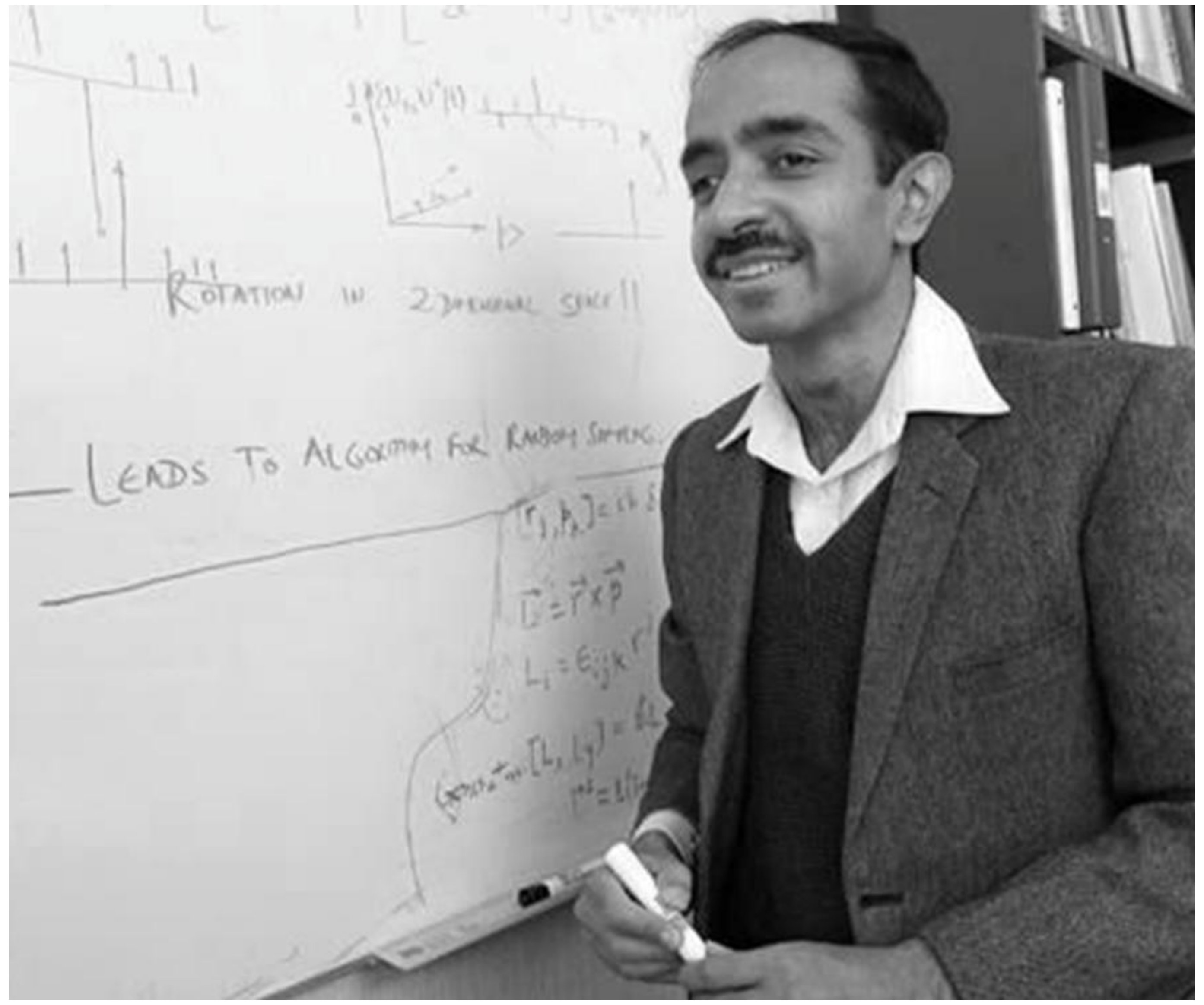
Craig Gidney @CraigGidney · Mar 15
Replying to @quantumVerd @KikeSolanoPhys and 4 others
The paper uses a cost model where quantum memory is comparatively cheap. I'd have included the mem qubit count in the title (at n=2048 there's 13K compute qubits and 430M mem qubits) but don't see anything wrong with considering a world where mem ends up cheaper than cpu.

Quantum search

Grover's algorithm (1996)

Searches in N items in $\sqrt{N}$ queries!

- AES-128 broken in $\sqrt{(2^{128})} = 2^{64}$ operations?
- Applications in machine learning models



Caveats:

- Constant factor in **O($\sqrt{N}$)** may be huge
- Doesn't parallelize as classical search does

Quantum-searching AES keys

	#gates		depth		#qubits
k	T	Clifford	T	overall	
128	$1.19 \cdot 2^{86}$	$1.55 \cdot 2^{86}$	$1.06 \cdot 2^{80}$	$1.16 \cdot 2^{81}$	$2,953$
192	$1.81 \cdot 2^{118}$	$1.17 \cdot 2^{119}$	$1.21 \cdot 2^{112}$	$1.33 \cdot 2^{113}$	$4,449$
256	$1.41 \cdot 2^{151}$	$1.83 \cdot 2^{151}$	$1.44 \cdot 2^{144}$	$1.57 \cdot 2^{145}$	6,681

Table 5. Quantum resource estimates for Grover's algorithm to attack AES-k, where $k \in \{128, 192, 256\}$.

https://arxiv.org/pdf/1512.04965v1.pdf

If gates are the size of a hydrogen atom (12pm) this depth is the **diameter of the solar system** (~10^{13}m), yet less than 5 grams

No doubt more efficient circuits will be designed…

Quantum-searching AES keys

From February 2020, better circuits found

Implementing Grover oracles for quantum key search on AES and LowMC

Samuel Jaques[1*†], Michael Naehrig[2], Martin Roetteler[3], and Fernando Virdia[4†‡]

scheme	r	#Clifford	$\#T$	$\#M$	T-depth	full depth	width	G-cost	DW-cost	p_s
AES-128	1	$1.13 \cdot 2^{82}$	$1.32 \cdot 2^{79}$	$1.32 \cdot 2^{77}$	$1.48 \cdot 2^{70}$	$1.08 \cdot 2^{75}$	1665	$1.33 \cdot 2^{82}$	$1.76 \cdot 2^{85}$	$1/e$
AES-128	2	$1.13 \cdot 2^{83}$	$1.32 \cdot 2^{80}$	$1.32 \cdot 2^{78}$	$1.48 \cdot 2^{70}$	$1.08 \cdot 2^{75}$	3329	$1.34 \cdot 2^{83}$	$1.75 \cdot 2^{86}$	1
AES-192	2	$1.27 \cdot 2^{115}$	$1.47 \cdot 2^{112}$	$1.47 \cdot 2^{110}$	$1.47 \cdot 2^{102}$	$1.14 \cdot 2^{107}$	3969	$1.50 \cdot 2^{115}$	$1.11 \cdot 2^{119}$	1
AES-256	2	$1.56 \cdot 2^{147}$	$1.81 \cdot 2^{144}$	$1.81 \cdot 2^{142}$	$1.55 \cdot 2^{134}$	$1.29 \cdot 2^{139}$	4609	$1.84 \cdot 2^{147}$	$1.45 \cdot 2^{151}$	$1/e$
AES-256	3	$1.17 \cdot 2^{148}$	$1.36 \cdot 2^{145}$	$1.36 \cdot 2^{143}$	$1.55 \cdot 2^{134}$	$1.28 \cdot 2^{139}$	6913	$1.38 \cdot 2^{148}$	$1.08 \cdot 2^{152}$	1

Eliminating the Problem: 256-bit Keys

Defeating Quantum Algorithms

A.k.a. “quantum-safe”, “quantum-resilient” ; must not rely on factoring or discrete log

Why bother?

Insurance against QC threat:

- “QC has a probability *p* work in year X and the impact would be $N for us”
- “I’d like to eliminate this risk and I’m ready to spend $M for it”

Supposedly the motivation of USG/NSA:

"we anticipate a need to shift to quantum-resistant cryptography in the near future.” — NSA in CNSS advisory 02-2015

NSA's Take (Aug 2021)

Q: Is NSA worried about the threat posed by a potential quantum computer because a CRQC exists?
A: NSA does not know when or even if a quantum computer of sufficient size and power to exploit public key cryptography (a CRQC) will exist.

Q: Why does NSA care about quantum computing today? Isn't quantum computing a long way off?
A: The cryptographic systems that NSA produces, certifies, and supports often have very long lifecycles. NSA has to produce requirements today for systems that will be used for many decades in the future, and data protected by these systems will still require cryptographic protection for decades after these solutions are replaced. There is growing research in the area of quantum computing, and global interest in its pursuit have provoked NSA to ensure the enduring protection of NSS by encouraging the development of post-quantum cryptographic standards and planning for an eventual transition.

Q: What are the timeframes in NSS for deployment of new algorithms, use of equipment, and national security information intelligence value?
A: New cryptography can take 20 years or more to be fully deployed to all National Security Systems. NSS equipment is often used for decades after deployment. National security information intelligence value varies depending on classification, sensitivity, and subject, but it can require protection for many decades.

https://media.defense.gov/2021/Aug/04/2002821837/-1/-1/1/Quantum_FAQs_20210804.pdf

The NIST competition

CSRC HOME > GROUPS > CT > POST-QUANTUM CRYPTOGRAPHY PROJECT

POST-QUANTUM CRYPTO PROJECT

NEWS -- August 2, 2016: The National Institute of Standards and Technology (NIST) is requesting comments on a new process to solicit, evaluate, and standardize one or more quantum-resistant public-key cryptographic algorithms. Please see the Post-Quantum Cryptography Standardization menu at left.

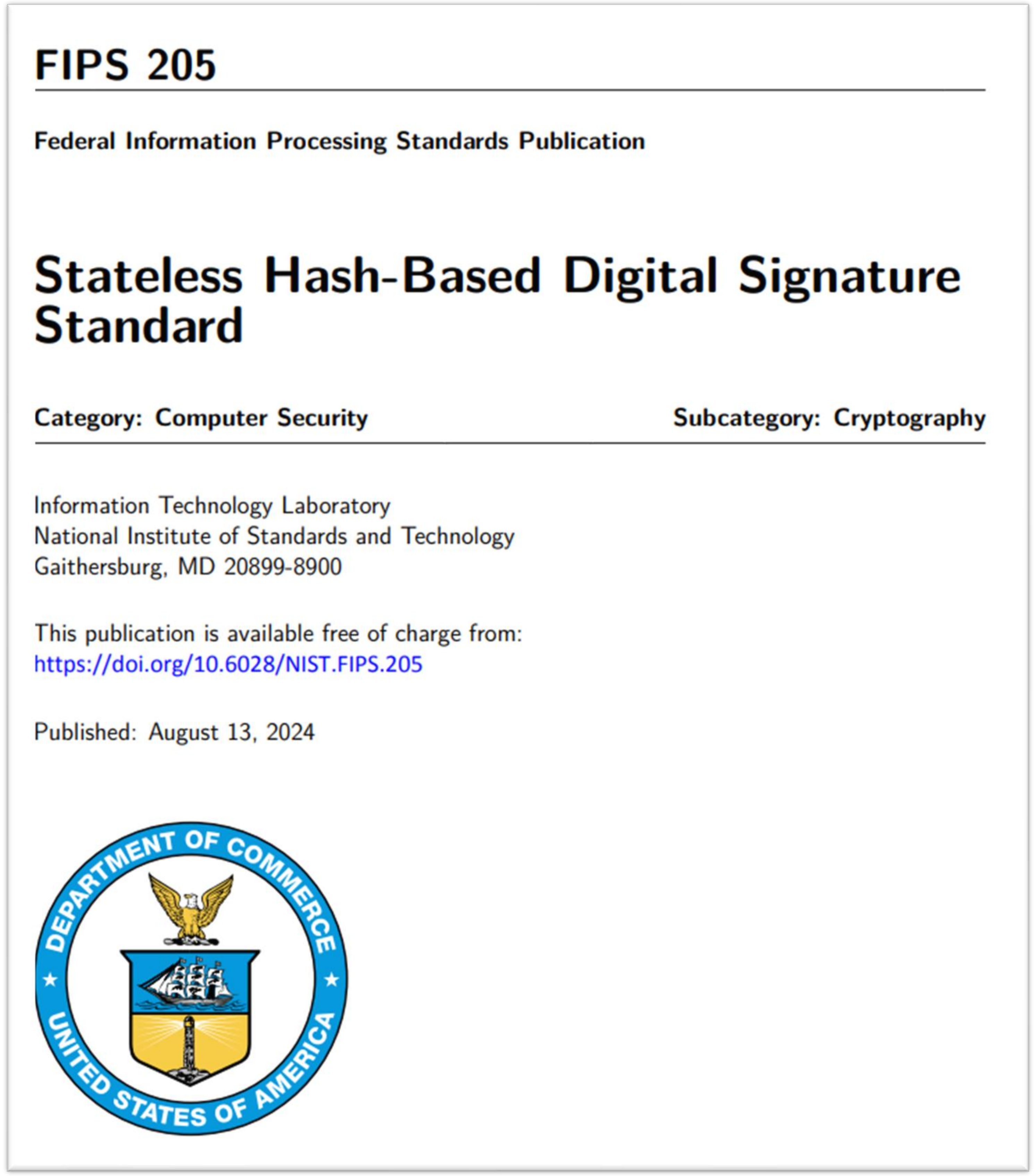
Fall 2016	Formal Call for Proposals
Nov 2017	Deadline for submissions
Early 2018	Workshop - Submitter's Presentations
3-5 years	Analysis Phase - NIST will report findings *1-2 workshops during this phase*
2 years later	Draft Standards ready

NIST standards and round 4

Standards announced in 2022:

- Encryption/KEM: **Kyber** (ML-KEM, FIPS 203)
- Signature:
  - **Dilithium** (ML-DSA, FIPS 204)
  - **Falcon** (*TBD*)
  - **SPHINCS+** (SLH-DSA, FIPS 205)

All *latticed-based* except SPHINCS+



FIPS 205

Federal Information Processing Standards Publication

Stateless Hash-Based Digital Signature Standard

Category: Computer Security   Subcategory: Cryptography

Information Technology Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899-8900

This publication is available free of charge from:
https://doi.org/10.6028/NIST.FIPS.205

Published: August 13, 2024

Round 4 only for encryption/KEM, all *code-based*:

~~BIKE, Classic McEliece~~, **HQC** selected as the winner in 2025

Lattice-based crypto intuition

Based on problems such as **learning with errors** (LWE):

S a secret vector of numbers

The attacker receives pairs of vectors (**A**, **B**)

- **A** = (A_0, …, A_{n-1}) is a vector of uniformly random numbers
- **B** = <**S**, **A**> + **E** , a vector of $B_i = S_i * A_i + E_i$
- **E** = (E_0, …, E_{n-1}) is an **unknown** vector or *normal*-random numbers

Attacker's goal: find **S** given many pairs (**A**, **B**)

Lattice-based crypto intuition

Based on problems such as **learning with errors** (LWE):

S a secret vector of numbers

The attacker receives pairs of vectors (**A**, **B**)

- **A** = ($\mathbf{A_0}$, …, $\mathbf{A_{n-1}}$) is a vector of uniformly random numbers
- **B** = <**S**, **A**> + **E** , a vector of $\mathbf{B_i}$ = $\mathbf{S_i}$*$\mathbf{A_i}$ + $\mathbf{E_i}$
- **E** = ($\mathbf{E_0}$, …, $\mathbf{E_{n-1}}$) is an **unknown** vector or *normal*-random numbers

Attacker's goal: find **S** given many pairs (**A**, **B**)

Without the errors **E**: trivial to solve (just a linear systems of equations)

With the errors **E**: **NP-hard**

PQC performance: pretty good!

Algorithm	Public key (bytes)	Ciphertext (bytes)	Key gen. (ms)	Encaps. (ms)	Decaps. (ms)	
ECDH NIST P-256	64	64	0.072	0.072	0.072	Elliptic curves (not post-quantum)
SIKE p434	330	346	13.763	22.120	23.734	Isogeny-based
Kyber512-90s	800	736	0.007	0.009	0.006	Lattice-based
FrodoKEM-640-AES	9,616	9,720	1.929	1.048	1.064	

Table 1: Key exchange algorithm communication size and runtime

Algorithm	Public key (bytes)	Signature (bytes)	Sign (ms)	Verify (ms)	
ECDSA NIST P-256	64	64	0.031	0.096	
Dilithium2	1,184	2,044	0.050	0.036	Lattice-based
qTESLA-P-I	14,880	2,592	1.055	0.312	
Picnic-L1-FS	33	34,036	3.429	2.584	Zero-knowledge proof-based

Table 2: Signature scheme communication size and runtime

From "Benchmarking Post-Quantum Cryptography in TLS” https://eprint.iacr.org/2019/1447

Using PQC today

Integrated by most **hyperscalers**

Cloudflare now uses post-quantum cryptography to talk to your origin server
2023-09-29

AWS Security Blog
Post-quantum TLS now supported in AWS KMS
by Andrew Hopkins | on 04 NOV 2019 | in Advanced (300), AWS Key Management Service, Security, Identity, & Compliance | Permalink | Comments | Share

Security & Identity
Announcing quantum-safe digital signatures in Cloud KMS
February 21, 2025

Software libraries

OpenSSL 3.5.0 now contains post-quantum procedures

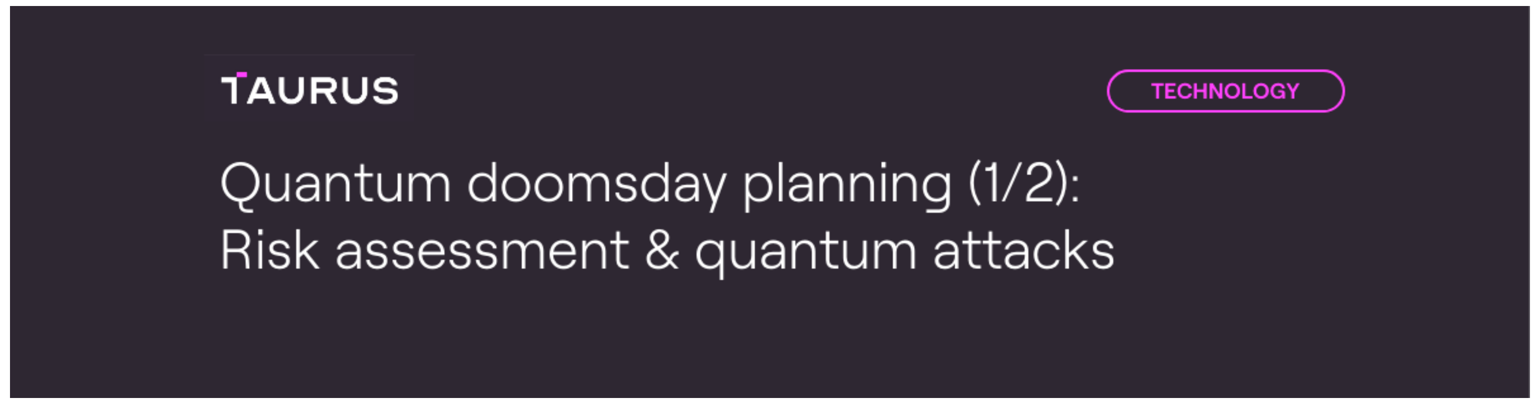
With the new LTS version 3.5.0, OpenSSL adds the post-quantum methods ML-KEM, ML-DSA and SLH-DSA to its library.

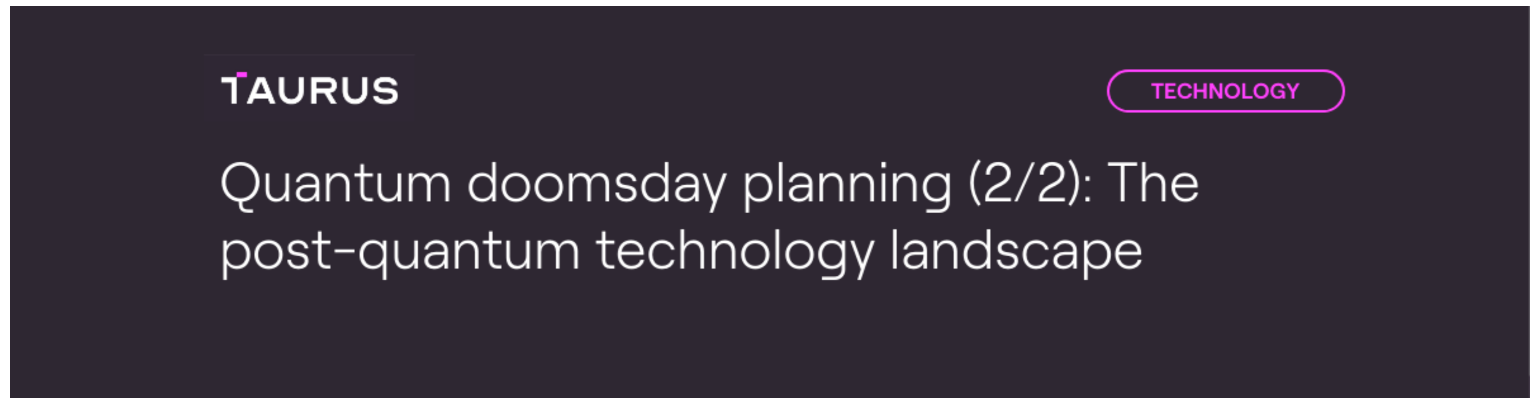
open-quantum-safe / **liboqs**
Code | Issues 19 | Pull requests 4 | Actions | Projects 0 | W
C library for quantum-safe cryptography. https://openquantumsafe.org/

mupq / **pqm4**
Code | Issues 3 | Pull requests 0 | Actions
Post-quantum crypto library for the ARM Cortex-M4

More about post-quantum crypto

- https://github.com/veorq/awesome-post-quantum
- https://github.com/qosf/awesome-quantum-software
- https://csrc.nist.gov/projects/post-quantum-cryptography/post-quantum-cryptography-standardization
- IETF RFC 8391 (XMSS), RFC 8554 (LM)
- May 2023 articles on https://blog.taurushq.com/





дякую!

jp@taurushq.com