Post-Quantum Cryptography

A Realistic Guide to Manage the Transition

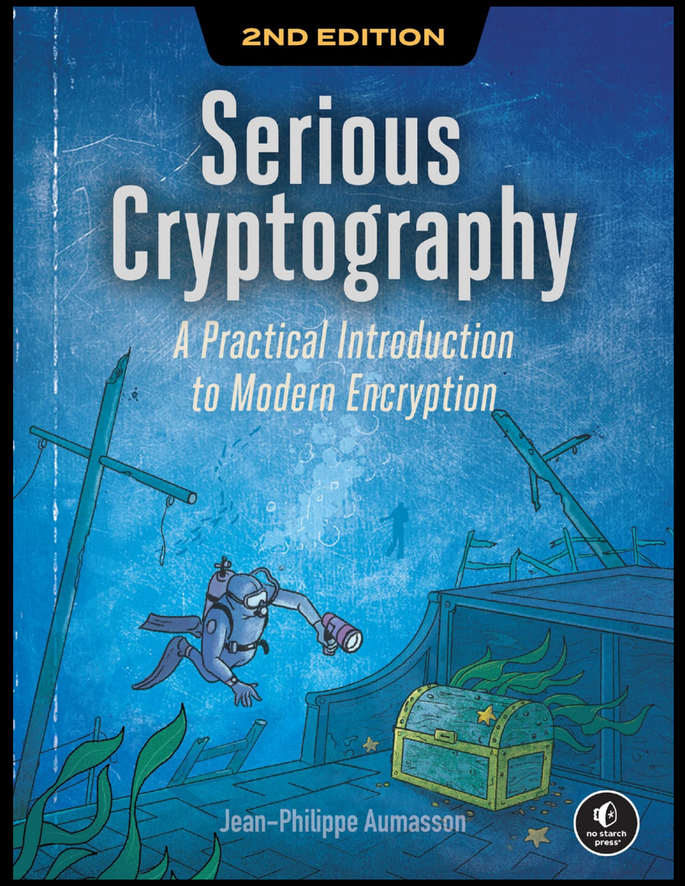
JP Aumasson

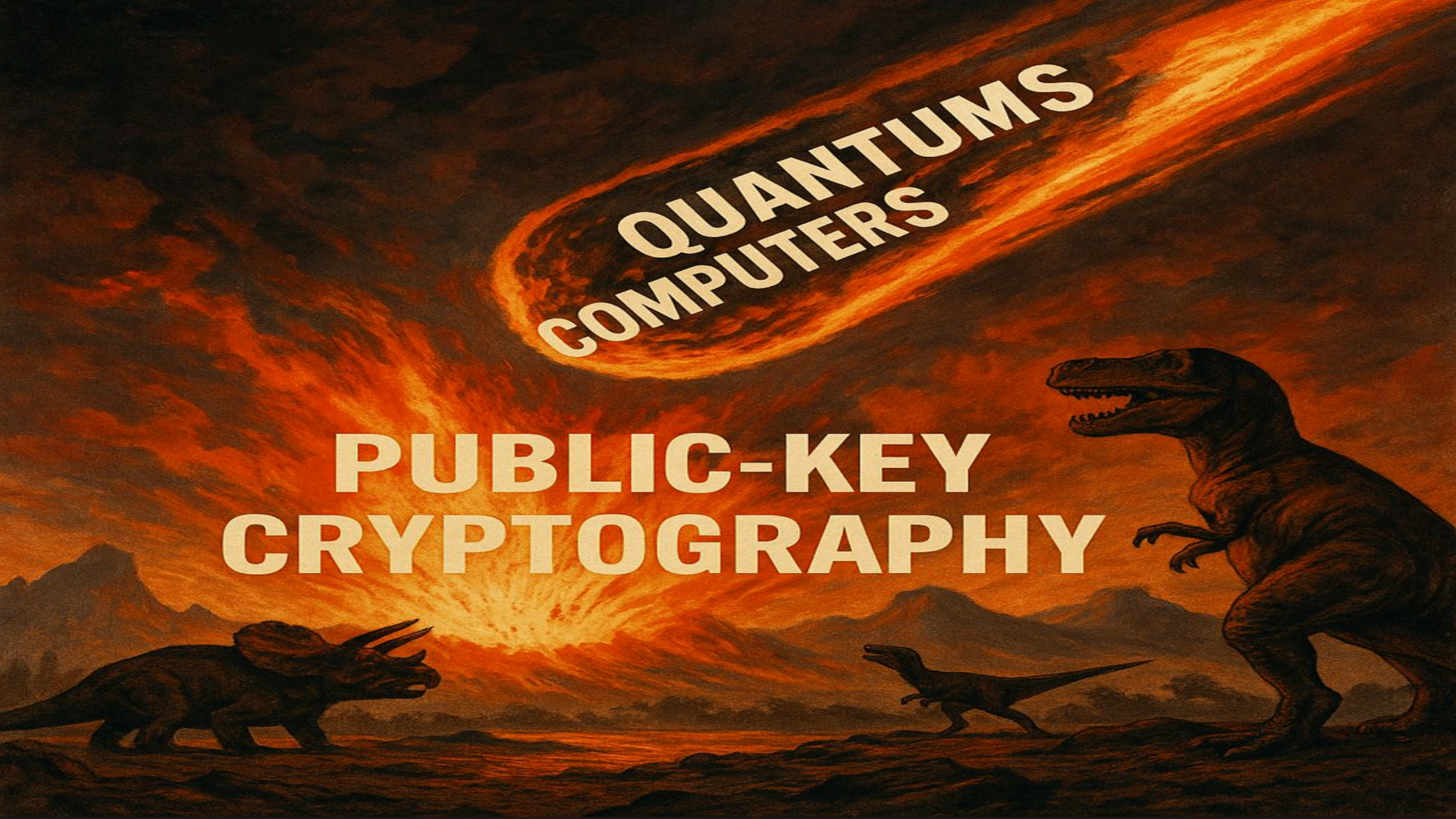
About me

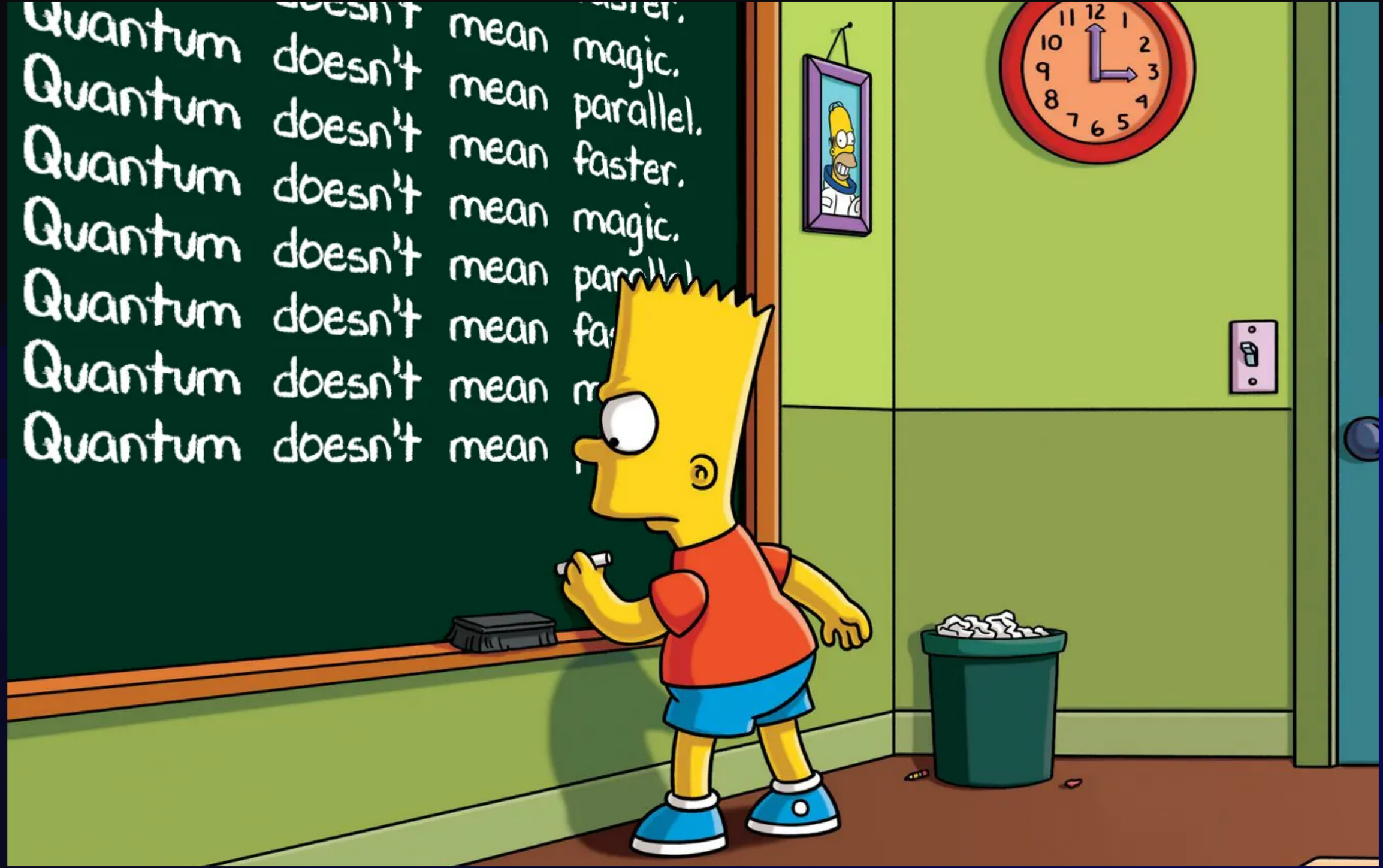
aumasson.jp | bfswa.substack.com | taurushq.com

TAURUS

- 20 years in cryptography & security
- Co-author BLAKE2/3, SipHash, **SLH-DSA**
- **Chief Security Officer** at Taurus SA
  - Crypto asset custody tech for banks
  - Managing **quantum risk** since 2018




QUANTUMS COMPUTERS
PUBLIC-KEY CRYPTOGRAPHY


Quantum doesn't mean magic.
Quantum doesn't mean parallel.
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Quantum computers

A different way to compute, using quantum mechanics

- NOT **faster** computers, in terms of clock cycle

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- NOT **trying-all-answers-simultaneously**

Quantum computers

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- Could only solve VERY FEW math problems, including
  - **Factoring**: find p and q given $n = p \times q$
  - **Discrete logarithm**: find d given x, p, and $y = x^d \bmod p$

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- 😱 These are the hard problems in RSA and elliptic curve schemes

This talk

1. How bad is it?
2. Post-quantum cryptography
3. Tech you can use today
4. Migration plan guidelines

1. How bad is it?

- 🍕 Impact on cryptography
- ⚛️ Quantum computers today
- 📣 Recent announcements
- 💰 The curious cryptocurrency case

Impact on cryptography (1/3)

Signature and authentication

Anything using RSA or elliptic curve crypto is broken:

- **Public-key infrastructure** (PKI): certificates, OCSP responses, CT logs
- **General infrastructure**: DNSSEC, BGP/RPKI, EMV payment
- **Code signing**: OS applications, firmware, APT/RPM packages, dependencies
- **Authentication** protocols: SSH host keys, FIDO2, client certs
- **Blockchain**: transaction signatures

Impact on cryptography (2/3)

Encryption keys generation/protection

Anything using RSA or elliptic curve crypto is broken:

- **Key establishment**: TLS, SSH, IPsec, WireGuard, messaging protocols
- **Encryption key wrapping**: PGP, S/MIME, KEK, ECIES
- **Protecting data confidentiality**, e.g. some privacy-oriented blockchains

“Collect now, decrypt later” applies, unlike signature/authentication

 Impact on cryptography (3/3)

Other cryptography

- **Multi-party computation** protocols such as
  - Threshold signing of ECDSA, Ed25519
  - Private set intersection, as used in iCloud
- Many **ZK proof** systems: blockchains' ZK rollups, zkVMs, privacy coins
- Most deployed **PAKEs** (password-based auth protocols), incl. OPAQUE
- **Anonymous credential** protocols, as Privacy Pass

Non-impact on cryptography

Symmetric cryptography vs. Grover's algorithm

There's a common misconception that quantum computers will "halve" the security of symmetric keys, requiring 256-bit keys for 128 bits of security. That is not an accurate interpretation of the speedup offered by quantum algorithms, it's not reflected in any compliance mandate, and risks diverting energy and attention from actually necessary post-quantum transition work. The misconception is usually based on a misunderstanding of the applicability of a different quantum algorithm, Grover's.

AES-128 is safe against quantum computers. SHA-256 is safe against quantum computers. No symmetric key sizes have to change as part of the post-quantum transition. This is a near-consensus opinion amongst experts and standardization bodies and it needs to propagate to the rest of the IT community. The rest of this article backs up this claim both technically and with references to relevant authorities.

words.filippo.io/128-bits/

⚛ Quantum computers today: ~100 qubits

Research prototypes of no practical interest yet

Most visible companies are **Google** “Quantum AI” and **IBM**, many others

Challenges:

- **Scale** to a large number of connected, entangled qubits
- Improve **coherence** time and the number of **quantum gates**
- Maintain low **error rate** and support quantum **error correction**

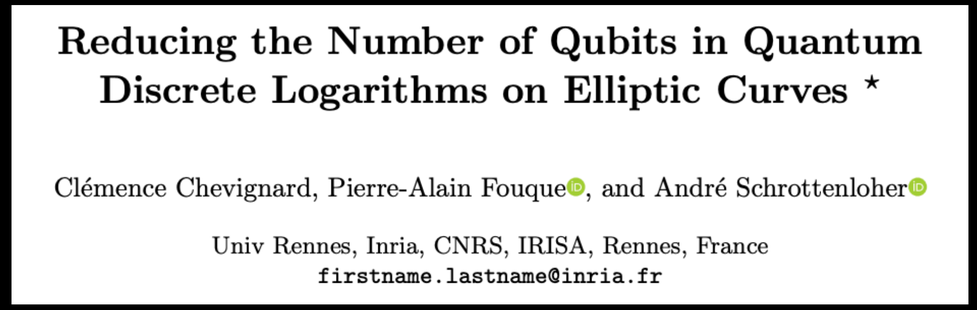
📣 Recent announcements (Google, March 30)

Reduced the number of quantum gates needed to break crypto

Actual algorithm **undisclosed** (evidence as a ZK proof)

*"[could] execute in minutes using fewer than **half a million** physical qubits"*

Builds upon the results from eprint.iacr.org/2026/280



📣 Recent announcements (Oratomic, March 30)

"Neutral atoms" approach may require even fewer qubits

Neutral atoms technology architecture

No hardware, only theoretical description

Quantum Physics

[Submitted on 30 Mar 2026]

Shor's algorithm is possible with as few as 10,000 reconfigurable atomic qubits

Madelyn Cain, Qian Xu, Robbie King, Lewis R. B. Picard, Harry Levine, Manuel Endres, John Preskill, Hsin-Yuan Huang, Dolev Bluvstein

2025 experiment with 6100 qubits, but:

- No entanglement, 13 seconds coherence
- No error correction implemented
- Not a quantum computer

Article | Open access | Published: 24 September 2025

A tweezer array with 6,100 highly coherent atomic qubits

Hannah J. Manetsch, Gyohei Nomura, Elie Bataille, Xudong Lv, Kon H. Leung & Manuel Endres

Nature **647**, 60–67 (2025) | Cite this article

When…

will a quantum computer break cryptography?

Nobody knows. Could be 2030, 2060, 2300, or never.

IMHO no “Q-Day” before 2040.

💰 The curious cryptocurrency case

Or “the quantum gravity principle"

"No quantum computer will ever be used to steal bitcoins”

- Price will **crash** if Bitcoin vulnerable AND a QC is **known/suspected** to exist
- A QC kept secret has much more valuable use than stealing cryptocurrency

Quantum computers will not steal your bitcoins, even if they can

The quantum gravity principle

NOV 13, 2025 · JP AUMASSON

bfswa.substack.com/p/quantum-computers-will-not-steal

2. Post-quantum cryptography

- 💡 What is PQC?
- 🦅 NIST standards and deadlines
- 🚀 Performance trade-offs
- 🦁 Regional PQC initiatives
- 🔒 PQ HTTPS adoption

💡 What is PQC?

a.k.a. quantum-safe or quantum-secure

Public-key crypto **not vulnerable** to quantum algorithms

- Must not rely on the hardness of factoring or discrete logarithm

💡 What is PQC?

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PQC relies on

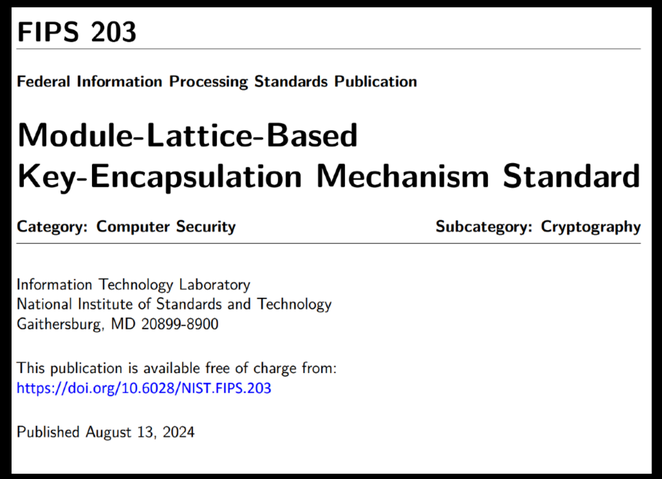
- Problems related to **NP-hard** problems (lattice, error correction)
- Breaking symmetric cryptography (like finding **hash function preimages**)
- Problems that we don’t know how to solve classically :)

NIST standards

De facto global PQC standards

Developed via a public competition (like AES and SHA-3) since 2016

Signature and **KEM** (key encapsulation mechanism)



FIPS 203

Federal Information Processing Standards Publication

Module-Lattice-Based Key-Encapsulation Mechanism Standard

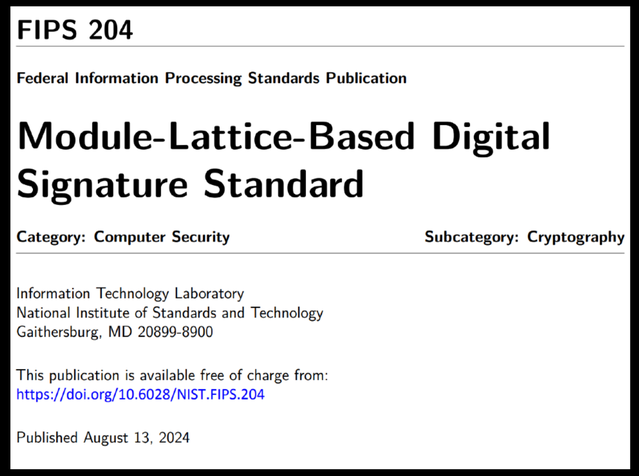
Category: Computer Security Subcategory: Cryptography

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.203

Published August 13, 2024

ML-KEM



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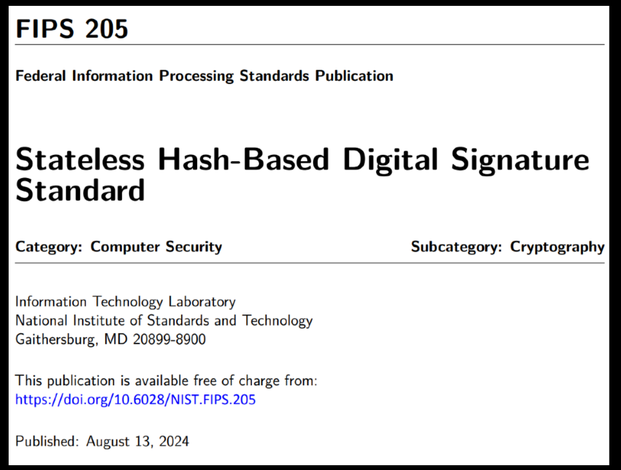
ML-DSA



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SLH-DSA

+ FN-DSA (signature)

+ "HQC" (KEM)

NIST deadlines

PQC must be deployed by 2035

In NIST IR 8547 "Transition to Post-Quantum Cryptography Standards”

Digital Signature Algorithm Family	Parameters	Transition
ECDSA [FIPS186]	112 bits of security strength	***Deprecated*** after 2030 ***Disallowed*** after 2035
	≥ 128 bits of security strength	***Disallowed*** after 2035
EdDSA [FIPS186]	≥ 128 bits of security strength	***Disallowed*** after 2035
RSA [FIPS186]	112 bits of security strength	***Deprecated*** after 2030 ***Disallowed*** after 2035
	≥ 128 bits of security strength	***Disallowed*** after 2035

Key Establishment Scheme	Parameters	Transition
Finite Field DH and MQV [SP80056A]	112 bits of security strength	***Deprecated*** after 2030 ***Disallowed*** after 2035
	≥ 128 bits of security strength	***Disallowed*** after 2035
Elliptic Curve DH and MQC [SP80056A]	112 bits of security strength	***Deprecated*** after 2030 ***Disallowed*** after 2035
	≥ 128 bits of security strength	***Disallowed*** after 2035
RSA [SP80056B]	112 bits of security strength	***Deprecated*** after 2030 ***Disallowed*** after 2035
	≥ 128 bits of security strength	***Disallowed*** after 2035

Federal agencies: mandated by OMB M-23-02 & NSM-10, enforced by **CISA**

🧬 Hybrid schemes

Best of both worlds

3.2. PQC-Classical Hybrid Protocols

The migration to post-quantum cryptography may initially include hybrid solutions that incorporate the use of quantum-resistant and quantum-vulnerable algorithms when establishing cryptographic keys or generating digital signatures. These hybrid solutions are typically designed to remain secure if at least one of the component algorithms is secure.

Hybrid key agreement can combine X25519 Diffie-Hellman and ML-KEM

ML-KEM may be used alone, non-hybrid, if aligned with the threat model

Hybrid less relevant for signatures: **security can be restored** with new signatures

🚀 Performance trade-offs

KEMs

Value (bytes)	ECDH P-256	ML-KEM-512 post-quantum	HQC-128 post-quantum
Public key	64	800	2,249
Private key	32	1,632	2,289
Ciphertext	65	768	4,481

- ML-KEM's speed **comparable** to ECDH, HQC orders of magnitude **slower**
- ML-KEM private key can be "compressed" to a 64-byte seed
- **Hybrid** cheap: ciphertext size dominated by the PQ part

🚀 Performance trade-offs

Signatures

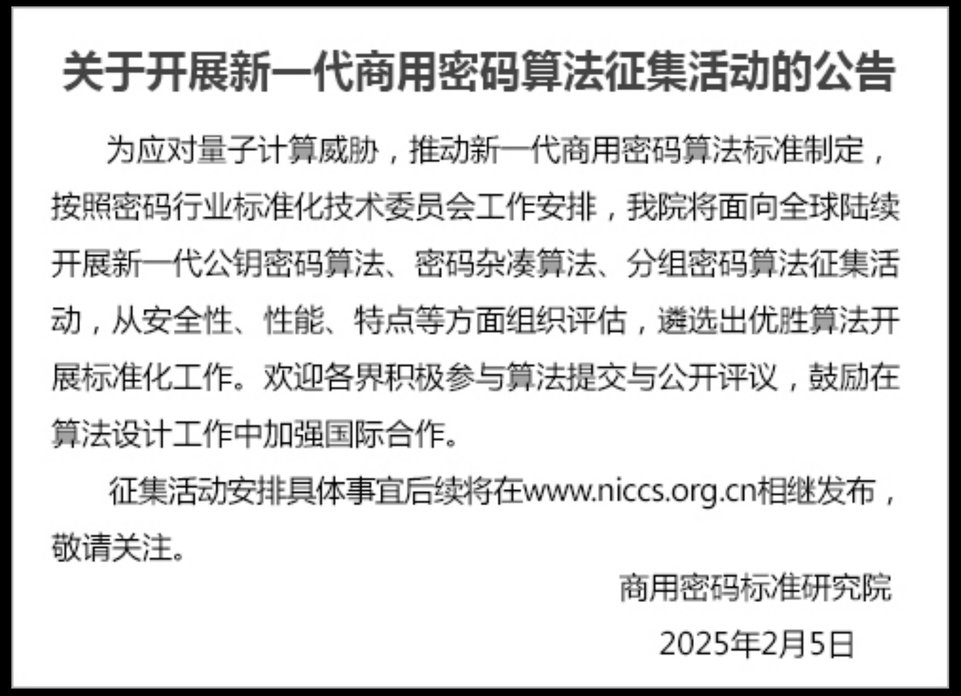
Value (bytes)	ECDSA P-256	ML-DSA-44 post-quantum	SLH-DSA-128s post-quantum
Public key	64	1,312	32
Private key	32	2,528	64
Signature	64	2,420	7,856

- ML-DSA's speed **comparable** to ECDSA, SLH-DSA orders of magnitude **slower**
- ML-DSA private key can be "compressed" to 32 bytes

🦁 Regional PQC initiatives

A short overview

- 🇨🇳 **China:** Competition program to select standards (NGCC) www.niccs.org.cn, submission deadline June 2026



关于开展新一代商用密码算法征集活动的公告

为应对量子计算威胁，推动新一代商用密码算法标准制定，按照密码行业标准化技术委员会工作安排，我院将面向全球陆续开展新一代公钥密码算法、密码杂凑算法、分组密码算法征集活动，从安全性、性能、特点等方面组织评估，遴选出优胜算法开展标准化工作。欢迎各界积极参与算法提交与公开评议，鼓励在算法设计工作中加强国际合作。

征集活动安排具体事宜后续将在www.niccs.org.cn相继发布，敬请关注。

商用密码标准研究院

2025年2月5日

Announcement on Launching the Next-generation Commercial Cryptographic Algorithms Program (NGCC)

In response to the threat of quantum computing and to promote the standardization of the next-generation commercial cryptographic algorithms, the Institute of Commercial Cryptography Standards (ICCS) is launching a global program to call for proposals for next-generation public-key cryptographic algorithms (NGCC-PK), cryptographic hash algorithms (NGCC-CH) and block cipher algorithms (NGCC-BC), according to the arrangement of Chinese Cryptography Standardization Technical Committee. The candidate algorithms will be evaluated in terms of security, performance and other features, and the finalists will be considered for standardization. ICCS looks forward to global algorithm submissions and comments, and encourages international cooperations in algorithm design.

Further notifications of the program will be released on *www.niccs.org.cn*

Institute of Commercial Cryptography Standards, China

February 5, 2025

🦁 Regional PQC initiatives

A short overview

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- 🇯🇵 **Japan:** No local standards, CRYPTREC (NIST equivalent) reviewed PQC algorithm, not formal guidelines yet www.cryptrec.go.jp

CRYPTREC 暗号技術ガイドライン（耐量子計算機暗号）2024年度版

🦁 Regional PQC initiatives

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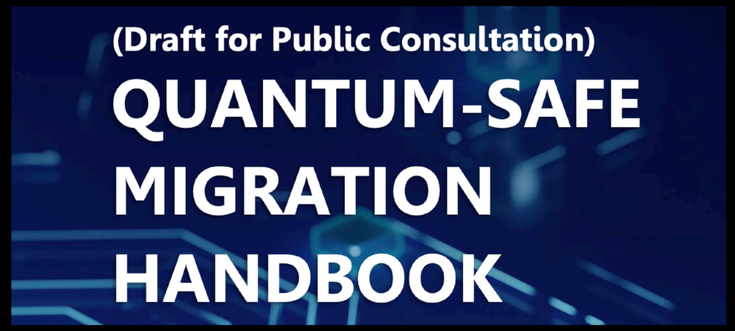
- 🇸🇬 **Singapore:** CSA Quantum-Safe Handbook and Readiness Index www.csa.gov.sg/resources/publications/quantum-safe-handbook-and-quantum-readiness-index/



CSA SINGAPORE Cyber Security Agency of Singapore · GOVTECH SINGAPORE · IMDA INFOCOMM MEDIA DEVELOPMENT AUTHORITY

Regional PQC initiatives

A short overview

Monetary Authority of Singapore

Quantum Security Questionnaire
April 2026

Quantum Security Questionnaire

HANDBOOK

READINES

3.3 Supply Chain Risk Assessment and Vendor Management

Question 10. Have you assessed quantum-related risks in your IT supply chain?

i. Comprehensive assessment completed
ii. Partial assessment conducted
iii. Assessment planned within next 12 months
iv. No assessment plans at the moment

Question 11. Have you engaged with your critical IT vendors regarding quantum-resistant solutions?

i. Yes, formal discussions initiated with all critical vendors
ii. Yes, discussions with some key vendors
iii. Preliminary inquiries made
iv. No engagement yet

Question 12. Do your new or upcoming vendor contracts include provisions for quantum-resistant solution migration?

i. Yes, all new contracts include such provisions
ii. Yes, some contracts include provisions
iii. Under consideration for future contracts

🦁 Regional PQC initiatives

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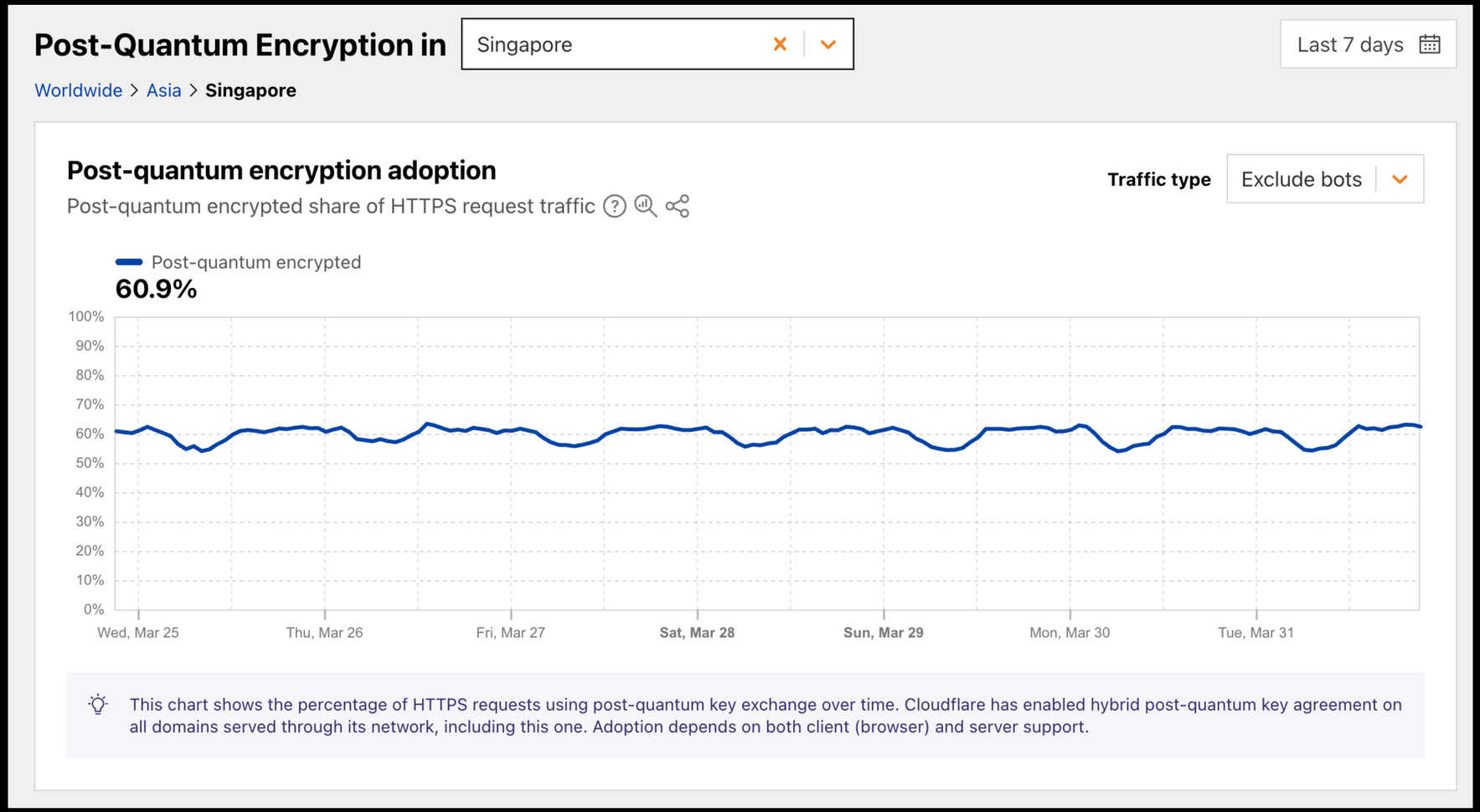
- 🇸🇬 **Singapore:** CSA Quantum-Safe Handbook and Readiness Index www.csa.gov.sg/resources/publications/quantum-safe-handbook-and-quantum-readiness-index/
- 🇰🇷 **South Korea**: KpqC competition kpqc.or.kr 2022-2025
  - KEM: NTRU+, SMAUG-T (lattice-based)
  - Signature: AIMer (**MitH**), HAETAE (lattice-based)

🔒 PQ HTTPS adoption (Singapore)

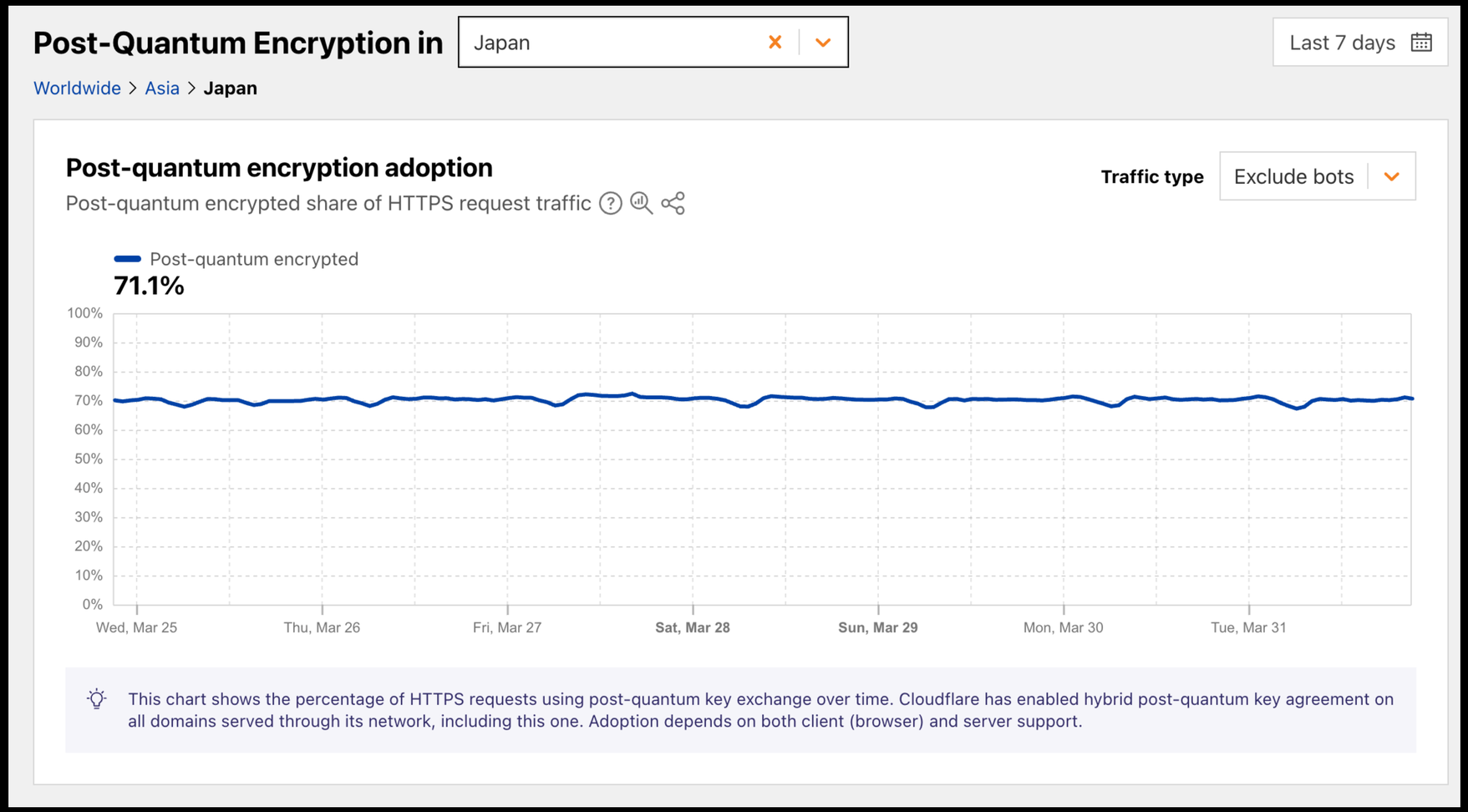
HTTPS traffic estimates by Cloudflare 🇸🇬



radar.cloudflare.com/post-quantum/sg

🔒 PQ HTTPS adoption (Japan)

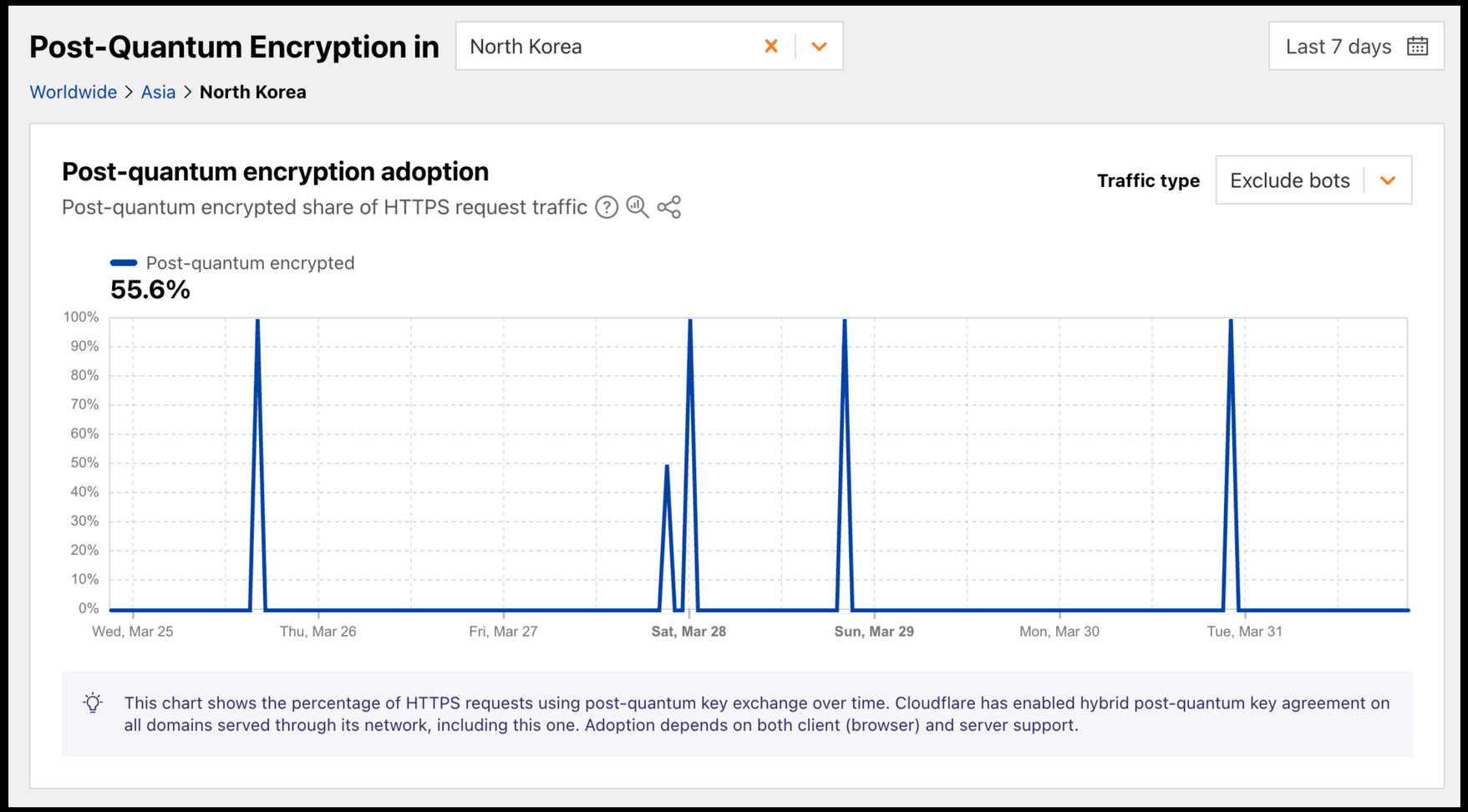
HTTPS traffic estimates by Cloudflare 🇯🇵



radar.cloudflare.com/post-quantum/jp

🔒 PQ HTTPS adoption (DPRK)

HTTPS traffic estimates by Cloudflare 🇰🇵



radar.cloudflare.com/post-quantum/kp

3. Tech you can use today

☁️ Cloud KMS
📱 Mobile platforms
🌐 Other infrastructure
⚙️ Open-source software

☁️ Cloud KMS

Key Management Services

- **AWS**: ML-DSA signing
- **Google**: ML-DSA signing, ML-KEM, X-Wing (hybrid KEM)
- **Azure**: no PQC support documented

Cloud HSMs back-ends don’t appear to support PQC yet (AWS in preview?)

Public API Client<> SaaS must be PQ: default in AWS and Google

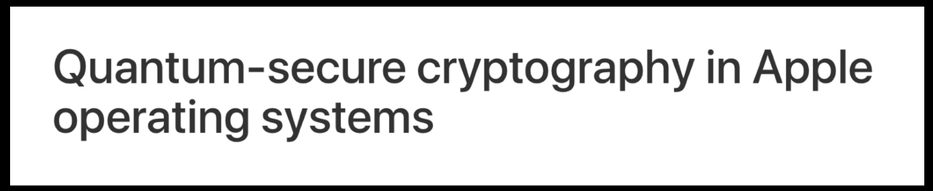
📱 Mobile platforms

iOS, Android

iOS 26

support.apple.com/guide/security/quantum-secure-cryptography-apple-devices-secc7c82e533/web

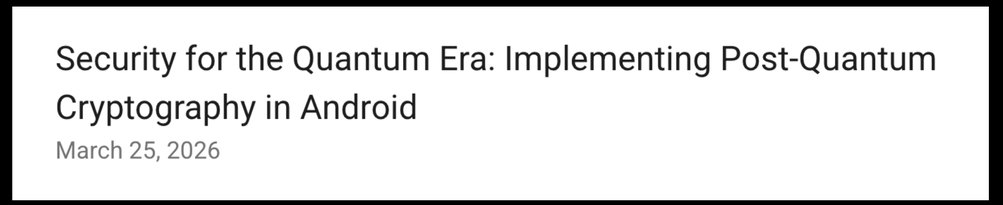
- TLS defaults to PQ KEM (via URLSession)
- CryptoKit API integrates ML-DSA and ML-KEM
- Secure Enclave support



Android 17

security.googleblog.com/2026/03/post-quantum-cryptography-in-android.html

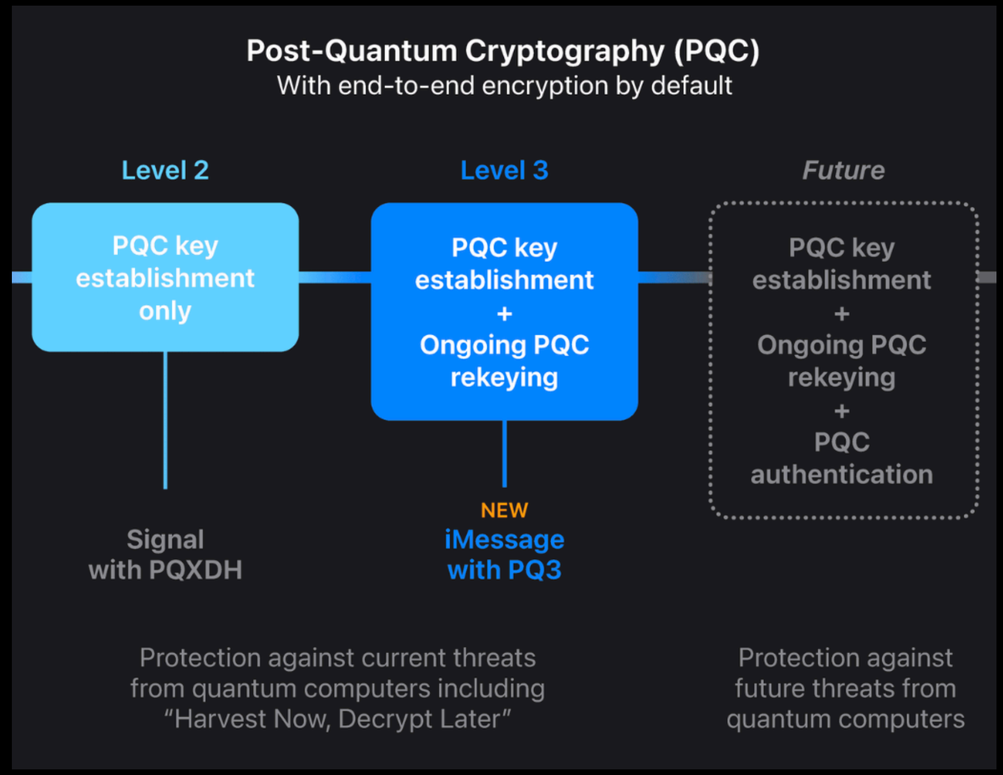
- ML-DSA in Keystore (via KeyPairGenerator)
- Bootloader integrity chain evolving to be PQ
- PQ TLS not enabled by default (custom Conscrypt needed)



🌐 Other infrastructure (1/3)

Apple

- **iMessage** is PQ (hybrid key agreement)
- **VPN** support (incl. IPsec API)
- Apple **Watch** <> iPhone comm is PQ



security.apple.com/blog/imessage-pq3/

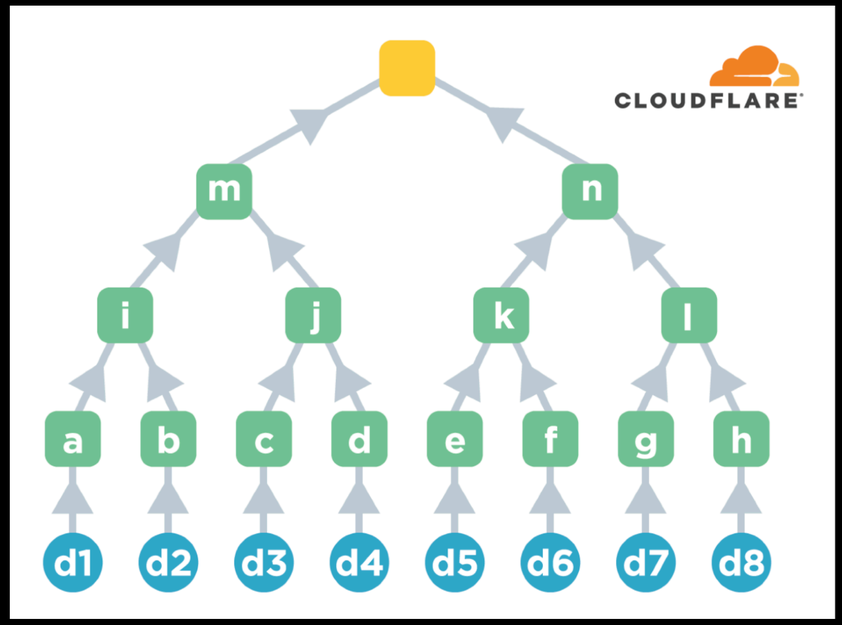
More in support.apple.com/guide/security/quantum-secure-cryptography-apple-devices-secc7c82e533/web

🌐 Other infrastructure (2/3)

Cloudflare

- Cloudflare **Tunnel** PQ by default
- PQ **TLS** 1.3 with hybrid key agreement
- Targets full product suite PQness by **2029**
- Co-introduced **Merkle Tree Certificates** for efficient PQ cert adoption

More in www.cloudflare.com/pqc/



https://blog.cloudflare.com/bootstrap-mtc/

🌐 Other infrastructure (3/3)

Other systems

- **HSMs**: most support some PQC; ACVP certificate but no FIPS-validated module
- **IPsec**: PQ key agreement defined for IKEv2, in strongSwan (not Libreswan)
- **Kubernetes**: TLS defaults to PQC via Go 1.24's TLS stack
- **Red Hat**: RHEL 10.1+'s DEFAULT policy uses PQC (SSH, TLS stacks)
- **Signal**: e2ee protocol PQ, via the PQXDH protocol (not the Noise transport)
- **WhatsApp**: NOT PQ yet

⚙️ Open-source software

Likely no need to write your own code

PQC software

- SUPERCOP - Benchmarks for cryptographic software

General-purpose libraries with PQC support

Does not include TLS implementations listed later:

- AWS-LC - Rust bindings in aws-lc-rs
- Botan - C++
- Bouncy Castle - Java/C#
- CIRCL (Cloudflare Interoperable, Reusable Cryptographic Library) - Go
- Google Tink - Multi-language (C++, Go, Java, Obj-C, Python)

TLS implementations with PQC support

- aws/s2n-tls
- BoringSSL
- OpenSSL
- Go crypto/tls
- wolfSSL

PQC libraries and language-specific software

C:

- algorand/falcon - Deterministic FALCON implementation
- liboqs - From Open Quantum Safe
- mupq/pqm4 - PQC library for the ARM Cortex-M4
- PQ Code Package - A Linux Foundation PQCA project building high-assurance imple track algorithms

Go:

- Go crypto/mlkem - Official Go implementation of Kyber/ML-KEM

JavaScript:

- paulmillr/noble-post-quantum - ML-KEM, ML-DSA, SLH-DSA, Falcon, and hybrids

.NET:

- Post-Quantum Cryptography in .NET

Rust:

- libcrux - Formally verified code
- RustCrypto/KEMs - ML-KEM, FrodoKem
- RustCrypto/signatures - ML-DSA, SLH-DSA, LMS

Zig:

- std.crypto - ML-DSA and ML-KEM in the standard library

github.com/veorq/awesome-post-quantum

4. Migration plan

👎 Find old crypto (inventory, CBOM)
👍 Replace with PQ crypto
🍻 Done!

4. Quantum risk management

🎯 General strategy
🔭 Observe
🔎 Assess
⚖️ Decide
🚀 Act & monitor

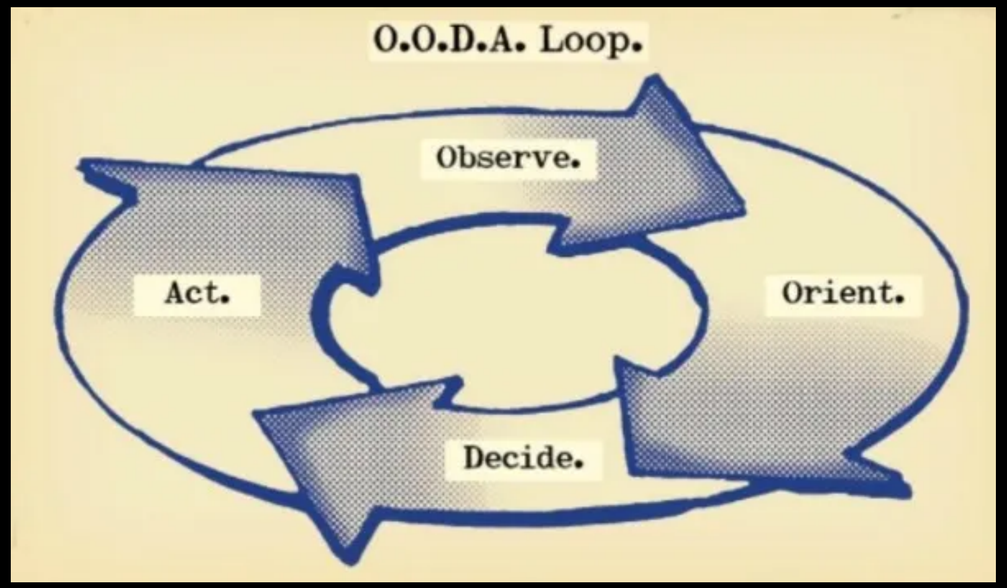
🎯 General strategy

Quantum risk management vs. migration

You can **migrate** a product or service to post-quantum cryptography

But for an organization, it's about **continuous quantum risk management**

- **Observe**: Where is crypto used?
- **Orient/assess**: How critical is it?
- **Decide**: What to do about it?
- **Act**: Communicate and apply changes



🔭 Observe

Identify the cryptography in your systems *and your suppliers'*

Confidentiality protection
Pubkey encryption & key agreement
KEMs, wrapping of symmetric keys

Encrypted files (if public-key protected)
On internal and shared filesystems, git repos, etc.

Encrypted email and messaging
PGP, S/MIME, messaging apps

Encrypted archives/back-ups
DB backups, cloud storage backups, etc.

Secure transport: TLS, SSH, IPsec, WireGuard, etc.
Pre-shared keys provide partial mitigation

PKI (unless pure auth/signature)
When keys used for key agreement, PGP encryption

KMS and HSM infrastructure
What are they used for & how are they protected

Blockchain & distributed ledger
Is data shared with other parties impacted? Incl. ZK proofs

Signature & Authentication
Access to critical systems must be a priority, even if "store now decrypt later" does not apply

Code signing (apps, bootloaders, etc.)
Esp. embedded systems with unupdatable integrity checks

PKI / Certificate chains
May include keys used for encryption

Authorization & authentication frameworks

🔭 Observe

Methods and tools

Internal systems, “easy”:

- Review documentation and policies (don’t modify them at this stage)
- Review configuration files and templates
- Verify alleged PQness on real live systems

Third-party products and services:

- Review documentation and technical settings
- Contact the vendor if needed, ask their PQC roadmap

Tools can help for code/config scan: cbomkit, ssh-audit, commercial solutions

🔭 Observe

Example SSH server PQC check: ssh-audit <host>

```
➜  ~ ssh-audit exe.xyz
# general
(gen) banner: SSH-2.0-SSHPiper
(gen) compatibility: OpenSSH 9.9+ (some functionality from 6.6), Dropbear SSH 2020.79+
(gen) compression: disabled

# key exchange algorithms
(kex) mlkem768x25519-sha256                -- [info] available since OpenSSH 9.9
                                           `- [info] hybrid key exchange based on post-quantum resistant
 algorithm and proven conventional X25519 algorithm
(kex) curve25519-sha256                    -- [info] available since OpenSSH 7.4, Dropbear SSH 2018.76
                                           `- [info] default key exchange from OpenSSH 7.4 to 8.9
(kex) curve25519-sha256@libssh.org         -- [info] available since OpenSSH 6.4, Dropbear SSH 2013.62
                                           `- [info] default key exchange from OpenSSH 6.5 to 7.3
```

🔎 Assess

Prioritize systems with respect to risk and cost

Risk criteria, for example:

- Data sensitivity lifetime
- Exposure outside the organization
- Assets volume and criticality (PII, key material, classification level)
- Regulatory compliance and contractual obligations

Cost criteria, for example:

- Technical difficulty (mere setting tweak vs. custom development)
- Impact on bandwidth and performance
- Interoperability and certification challenges

⚖️ Decide

Which systems to prioritize, which algorithms

Updates to make to **documentation** and control frameworks:

- Cryptography policy: newly deployed crypto must be PQ
- Key management procedures: adapt to PQC
- Requirements for suppliers and third-party software

Establish/update your **roadmap**:

- Milestones, from quick wins to multi-year efforts
- Roles & responsibilities
- Deprecation deadlines

🚀 Communicate

To all parties concerned

Internal:

- **Board/management**: “we have a plan”
- **Engineers**: requirements for TLS, SSH, etc.: point to libraries, code examples
- **Procurement/TPRM/legal**: requirements for new vendors

External:

- **Retail clients/users**: public roadmap overview
- **Enterprise clients**: detailed internal documents (crypto policy, etc.)
- **Partners/suppliers**: PQ requirements, plan joint upgrade operations

🚀 Act

Plan, develop, test, deploy, pray it actually works

You won’t see the end of your PQC program, as legacy crypto will be around for a while, thus the **quantum risk management** program

Create processes for continuous loop implementation:

- Add **discovery** controls: scans, audits, etc.
- Include quantum risk in the **risk management** model
- Evaluate **new** features and providers wrt PQC
- Plan **contingencies** if critical data is decrypted later

Conclusion

- No need to panic 🌿
- **Integrate** PQC support in your systems
- **Manage** the risk in your organization

Visit **github.com/veorq/awesome-post-quantum**

- NIST and IETF standards
- Regional migration guidelines
- Tech providers documentation
- Open-source software list

Credits

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Thank you!

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