The migration to post-quantum cryptography

Peter Schwabe

Max Planck Institute for Security and Privacy

November 14, 2025

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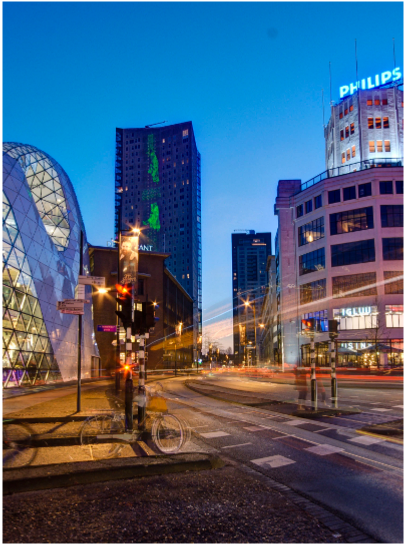

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- **Since 2013: Nijmegen**
  From Assistant to Full Professor

Since Sep. 2020: MPI-SP

- Located in **Bochum**
- Founded in 2019
- Currently 13 PIs

- Aim to have
  - 6 Departments
  - 12 Research Groups
  - Around 250 people total

Since Sep. 2020: MPI-SP

[A small demo]

DLP and factoring

Discrete Logarithms

- X25519 is Diffie-Hellman key exchange
- (More specifically, elliptic-curve DH)
- Relies on hardness of **discrete-logarithm problem (DLP)**
- Also signature algorithms from (EC)DLP: DSA, ECDSA, EdDSA

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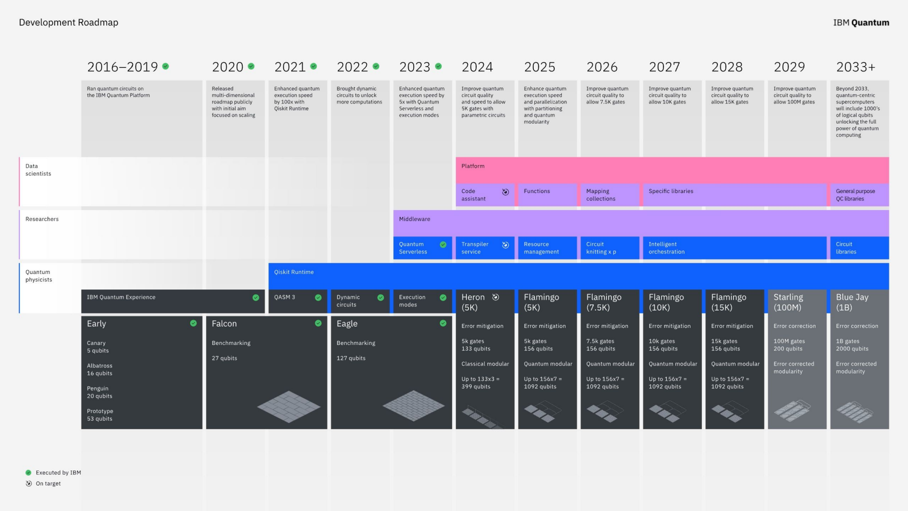
- Most of today’s key agreement and signatures use (EC)DLP or factoring-based schemes
- DLP and Factoring are related $\rightarrow$ we have a **crypto monoculture**

Polynomial-Time Algorithms for Prime Factorization and Discrete Logarithms on a Quantum Computer*

Peter W. Shor†

Abstract

A digital computer is generally believed to be an efficient universal computing device; that is, it is believed able to simulate any physical computing device with an increase in computation time by at most a polynomial factor. This may not be true when quantum mechanics is taken into consideration. This paper considers factoring integers and finding discrete logarithms, two problems which are generally thought to be hard on a classical computer and which have been used as the basis of several proposed cryptosystems. Efficient randomized algorithms are given for these two problems on a hypothetical quantum computer. These algorithms take a number of steps polynomial in the input size, e.g., the number of digits of the integer to be factored.



See https://www.ibm.com/quantum/blog/ibm-quantum-roadmap-2025

“Our conservative estimate is that cryptographically relevant quantum computers are likely to be available within 16 years.”

—BSI: The status of quantum computer development, Jan. 2025

Definition

Post-quantum crypto is (asymmetric) crypto that resists attacks using classical *and quantum* computers.

Post-quantum crypto (PQC)

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5 main directions

- Lattice-based crypto (PKE and Sigs)
- Code-based crypto (mainly PKE)
- Multivariate-based crypto (mainly Sigs)
- Hash-based signatures (only Sigs)
- Isogeny-based crypto (it's complicated. . .)

Should you care now?

"Harvest now, decrypt later"

https://en.wikipedia.org/wiki/Utah_Data_Center#/media/File:EFF_photograph_of_NSA's_Utah_Data_Center.jpg

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Mosca's theorem

$$X + Y > Z$$

- X: For how long do you need encrypted data to be secure?
- Y: How long does it take you to migrate to PQC
- Z: Time it will take to build a cryptographically relevant quantum computer

If $X + Y > Z$, you should worry.

Should you care now? (part II)

MOTORRAD

Menü

MOTORRAD Pur | Neuheiten | Motorräder | Bekleidung | Zubehör | Reisen | **Ratgeber** | Sport & Szene | Club | Markt

STARTSEITE > Ratgeber > Verkehr & Wirtschaft > Motorräder in Deutschland: Im Schnitt 19 Jahre alt

MOTORRÄDER IN DEUTSCHLAND SIND MEISTENS ALT

Motorräder: Im Durchschnitt grad erwachsen

Youngtimer dominieren: In Deutschland sind zugelassene Motorräder im Schnitt 19,1 Jahre alt.

Jens Kratschmar • 09.08.2022

The NIST PQC “not-a-competition”

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  - SHA3, running from 2007 to 2012

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- Selection through an open process and multiple rounds
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- PQC project:
  - Announcement: Feb 2016
  - Call for proposals: Dec 2016 (based on community input)
  - Deadline for submissions: Nov 2017

NIST PQC – how it started (Nov. 2017)

Count of Problem Category	Column Labels		
Row Labels	Key Exchange	Signature	Grand Total
?	1		1
Braids	1	1	2
Chebychev	1		1
Codes	19	5	24
Finite Automata	1	1	2
Hash		4	4
Hypercomplex Numbers	1		1
Isogeny	1		1
Lattice	24	4	28
Mult. Var	6	7	13
Rand. walk	1		1
RSA	1	1	2
Grand Total	**57**	**23**	**80**

Overview tweeted by Jacob Alperin-Sheriff on Dec 4, 2017.

NIST PQC – first results (Jul. 2022)

4 schemes selected for standardization

- **CRYSTALS-Kyber**: lattice-based key agreement
- **CRYSTALS-Dilithium**: lattice-based signatures
- Falcon: lattice-based signatures
- **SPHINCS$^+$**: hash-based signatures

4 schemes advanced to round 4

- Classic McEliece: code-based key agreement
- BIKE: code-based key agreement
- HQC: code-based key agreement
- SIKE: isogeny-based key agreement (**†** 30.07.2022)

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- **Additionally (June 2023):** 40 new signature submissions

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Yet, **full break without any "warning"**

More NIST PQC

- First three standards released in August 2024:
  - ML-KEM (CRYSTALS-Kyber)
  - ML-DSA (CRYSTALS-Dilithium)
  - SLH-DSA (SPHINCS$^+$)
- October 2024: 14 on-ramp signatures advanced to round 2
- March 2025: HQC selected for standardization (concludes round 4)
- FN-DSA (Falcon) standard draft almost ready

Summary of NIST PQC (so far)

Key agreements standards

- **ML-KEM**
- HQC

Signature standards

- **ML-DSA**
- **SLH-DSA**
- FN-DSA

Summary of NIST PQC (so far)

"The public-key encryption and key-establishment algorithm that will be standardized is CRYSTALS-KYBER. The digital signatures that will be standardized are CRYSTALS-Dilithium, FALCON, and SPHINCS$^+$. While there are multiple signature algorithms selected, NIST recommends CRYSTALS-Dilithium as the primary algorithm to be implemented"

—NIST IR 8413-upd1

BSI recommendations

Key agreements standards

- ML-KEM
- Classic McEliece (code-based, in standardization by ISO)
- FrodoKEM (lattice-based, in standardization by ISO)

Signature standards

- ML-DSA
- SLH-DSA
- XMSS and LMS (*stateful*, also standardized by IETF & NIST)

"Post-quantum schemes should only be used in combination with classical schemes ("hybrid") if possible."

—Recommendations by the BSI

https://www.bsi.bund.de/EN/Themen/Unternehmen-und-Organisationen/Informationen-und-Empfehlungen/Quantentechnologien-und-Post-Quanten-Kryptografie/quantentechnologien-und-post-quanten-kryptografie_node.html

Motivation for hybrid deployments

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  - Late breaks of GeMSS and Rainbow

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- Cryptanalysis of PQ schemes is not as stable as for ECC
  - SIKE. . . (was deployed, **hybrid**, by Google and Cloudflare)
  - Late breaks of GeMSS and Rainbow
- Implementation security of PQ schemes is not as mature as for ECC
  - Side-channel protection for ECC based on rich algebraic structure
  - For lattices: mostly masking + shuffling
  - Continued successful SCA against *protected* implementations
  - Compilers screwing with code in new ways ("Kyberslash")

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Sizes

- PQC cryptographic objects are much bigger than for ECC
- X25519 PK: 32 B
- Additing 32 Bytes to 1KB makes a small difference

Hybrid and the NIST competition

"NIST recognizes that some users may wish to deploy systems that use "hybrid modes," which combine post-quantum cryptographic algorithms with existing cryptographic algorithms (which may not be post-quantum). These "hybrid modes" are outside of the scope of this document, which is focused on post-quantum cryptographic algorithms only.

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  - Long discussions if Kyber512 meets level-1 security
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- For targeted hybrid deployment, designs could have (and would have!) made other choices

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How hard can this be?

[Answer 1: Back to our demo]

Answer 1: more positive examples

https://radar.cloudflare.com/adoption-and-usage#post-quantum-encryption-adoption

- Hundreds of billions of connections per day at Cloudflare alone
- Also used in secure messaging (Signal, iMessage)
- Also in cloud infrastructure (AWS)
- Signatures deployed in automotive SW updates and for secure boot

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Replacing MD5 was “easy”!

What lessons can we learn from this?

1. Migrating some (many?) applications to PQC is easy.
   - You are already using PQC, possibly without knowing!
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Creating a CBOM and “easy wins” can (and should!) be done in parallel

Start “playing” with PQC

SSH

- OpenSSH 10.0 uses MLKEM768-X25519 as default key agreement
- Released in April 2025
- Already in Debian stable (trixie)

Start "playing" with PQC

HTTPS (nginx+OpenSSL)

- OpenSSL 3.5 has support for MLKEM768-X25519
- Released in April 2025
- Already in Debian stable (trixie)
- Instructions for setting up NGINX (can probably skip compilation from source): https://www.linode.com/docs/guides/post-quantum-encryption-nginx-ubuntu2404/
- Client-side supported by all major browsers

Start “playing” with PQC

Post-quantum VPN on top of WireGuard

`https://rosenpass.eu`

Thank you!

https://cryptojedi.org