Engineering Post-Quantum Cryptography

May 4, 2022
A brief introduction

- 2001–2007: Aachen
A brief introduction

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• 2008–2011: Eindhoven
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• 2011–2012: Taipei
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• 2008–2011: Eindhoven
• 2011–2012: Taipei
• Since 2013: Nijmegen
Since Sep. 2020: MPI-SP
Since Sep. 2020: MPI-SP
Connection Encrypted (TLS_ECDHE_RSA_WITH_AES_256_GCM_SHA384, 256 bit keys, TLS 1.2)

The page you are viewing was encrypted before being transmitted over the internet. Encryption makes it difficult for unauthorized people to view information traveling between computers. It is therefore unlikely that anyone read this page as it traveled across the network.
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.
“In the past, people have said, maybe it’s 50 years away, it’s a dream, maybe it’ll happen sometime. I used to think it was 50. Now I’m thinking like it’s 15 or a little more. It’s within reach. It’s within our lifetime. It’s going to happen.”

—Mark Ketchen (IBM), Feb. 2012, about quantum computers
Post-quantum crypto

Definition
Post-quantum crypto is (asymmetric) crypto that resists attacks using classical and quantum computers.
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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 (so far, mainly PKE)
The NIST PQC “not-a-competition”

• Inspired by two earlier NIST crypto competitions:
  • AES, running from 1997 to 2000
  • SHA3, running from 2007 to 2012
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- Approach: NIST specifies criteria, everybody is welcome to submit proposals
- Selection through an open process and multiple rounds
- Actual decisions are being made by NIST
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- PQC project:
  - Announcement: Feb 2016
  - Call for proposals: Dec 2016 (based on community input)
  - Deadline for submissions: Nov 2017
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Overview tweeted by Jacob Alperin-Sheriff on Dec 4, 2017.
The NIST competition: Jan 2019

- Announcement planned at Real-World Crypto 2019
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Encryption / Key agreement

- 9 lattice-based
- 7 code-based
- 1 isogeny-based
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- 9 lattice-based
- 7 code-based
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**Signature schemes**

- 3 lattice-based
- 2 symmetric-crypto based
- 4 MQ-based
The NIST competition: Jul 2020

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**Finalists**

- 4 key-agreement schemes
  - 3 lattice-based
  - 1 code-based
- 3 signature schemes
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Finalists
- 4 key-agreement schemes
  - 3 lattice-based
  - 1 code-based
- 3 signature schemes
  - 2 lattice-based
  - 1 MQ-based

Alternate schemes
- 5 key-agreement schemes
  - 2 lattice-based
  - 2 code-based
  - 1 isogeny-based
- 3 signature schemes
  - 2 symmetric-crypto based
  - 1 MQ-based
The NIST competition right now

“Yes - the 3rd round will shortly be ending. NIST is actively writing the 3rd Round report which will explain our rationale for which algorithms we will standardize. We hope to be able to announce the results and report not later than the end of March.”

—Dustin Moody (NIST), Feb 9, 2022
"We wanted to give another quick update.

We’ve received a few inquiries about whether NIST’s talk at the PKC conference next week will be where we announce the candidates we will select for standardization. The short answer is no - it will not be.

We are still hoping to make our announcement by the end of this month (March)."

—Dustin Moody (NIST), Mar 4, 2022
“Another update:

We had been hoping to announce the results of our PQC standardization process by the end of March. We ask for a little bit more patience since we are not ready to make the announcement today. We still expect to make it very soon.”

—Dustin Moody (NIST), Mar 31, 2022
“Everybody,

We appreciate your patience. The announcement of the algorithms we will standardize is still coming very soon. This is a major milestone of our project, and the delay is not due to technical considerations but is due to some legal and procedural steps that are taking more time than we anticipated. Again, thank you for your patience.”

—Dustin Moody (NIST), Apr 19, 2022
The NIST competition right now

Expectation

• NIST is expected to announce winners very soon
• ≈ one year later get standards
The NIST competition right now

Expectation

- NIST is expected to announce winners *very soon*
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- Replace existing crypto with new crypto
The NIST competition right now

Expectation

• NIST is expected to announce winners very soon
• ≈ one year later get standards
• Replace existing crypto with new crypto

Mission accomplished – The world is safe again!

... or is it?
A bit of history: the case of MD5

• MD5 is a cryptographic hash function
• Hash functions are used as building blocks all over the place
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- **2012**: Flame malware exploits MD5 weaknesses

Replacing MD5 was “easy”!
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Challenge 1: Performance

- 10% performance difference matters!
  - Reduce cost for busy servers
  - Fit into constrained devices
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  - Reduce cost for busy servers
  - Fit into constrained devices
- Small routines executed many times
- Often hand-optimized on assembly level
Elliptic-curve cryptography

- State of the art today (but broken by Shor)
Elliptic-curve cryptography

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- Operations cost 50–200 kcycles (typical x64 CPU)

PQC performance examples

- McEliece public-key: \( \approx 0.5 \) MB
- SPHINCS signatures: \( \approx 16 \) KB
- SPHINCS signing: \( \approx 3 \) billion cycles
- Kyber (all ops): < 80 kcycles
- Kyber data sent: < 1.2 KB
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“An attacker who can break the security can also solve some hard mathematical problem”
Challenge 2: Security

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Great idea
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Great idea, but . . .

• reductions are often not tight
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Security reductions
“An attacker who can break the security can also solve some hard mathematical problem”

Great idea, but...

- reductions are often not tight
- “hard problem” may turn out to be easier than expected
- proofs may be wrong
The case of OCB2

- 2004: Rogaway proposes OCB2
  - Security reduction guaranteeing confidentiality and authenticity
- 2009: OCB2 is standardized by ISO
- 26 Oct. 2018: Break of authenticity by Inoue and Minematsu
- 8/11 Nov. 2018: Break of confidentiality by Poettering / Iwata
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Some NIST PQC proof failures

- Round-1 Kyber proof does not apply
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- Round-2 MQDSS attack “hidden inside non-tightness”
- Round-2 qTesla proof wrong (?) → devastating attack
Challenge 3: Implementation Security

• Attackers see more than input/output:
  • Power consumption
  • Electromagnetic radiation
  • Timing

• Side-channel attacks:
  • Measure information
  • Use to obtain secret data

• Timing attacks can be done remotely
• Cost of countermeasures heavily depends on the scheme
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“the implementation security aspect of lattice-based cryptography is still a vastly unexplored and open topic”

— Primas, Pessl, Mangard, 2017.
Challenge 3: Implementation Security (ctd.)

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- Other “realms” of PQC less explored than lattices
- Even for lattices still very much an open topic
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For many applications, implementations are not ready.
Challenge 4: The curious case of Diffie-Hellman

Alice

\[ A \leftarrow g^a \]

Bob

\[ B \leftarrow g^b \]

\[ K \leftarrow B^a = (g^b)^a = g^{ab} \]

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KEMs: as close as you’ll get to DH

Initiator

$$(pk, sk) \leftarrow \text{KEM.Gen}$$

Responder

$$\text{pk}$$

$$(ct, K) \leftarrow \text{KEM.Enc(pk)}$$

$$\text{ct}$$

$$K \leftarrow \text{KEM.Dec}(ct, sk)$$

Except with CSIDH (Castryck, Lange, Martindale, Renes, Panny, 2018)
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Challenge 5: “Huge foot cannons”

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- Hash-based signatures XMSS and LMS
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- Hash-based signatures XMSS and LMS
  - Reasonable performance
  - Reasonable signature sizes
  - Small keys

Caveat: They are stateful
- Need to update the secret key for every signing
- Updates are as easy as 1 – 2 – 3...
- Must never go back to earlier state!

Now combine this with, e.g., backups, VMs...

“It’s a huge foot cannon” — Adam Langley
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Is it already too late?

- Let’s assume that today’s crypto is broken in 15 years
- When do we need to start migrating?
Is it already too late?

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• When do we need to start migrating?
• Consider the following attack against confidentiality
  • Record encrypted message today
  • Decrypt in 15 years using quantum computer
Is it already too late?

• Let’s assume that today’s crypto is broken in 15 years
• When do we need to start migrating?
• Consider the following attack against confidentiality
  • Record encrypted message today
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How long do we need today’s communication to be secure?

How long does it take us to migrate?
But for signatures we have time, right?

- Signatures provide authentication
- Cannot retroactively “decrypt” anything
- Stop accepting pre-quantum signatures once there is a quantum computer
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- Will we know when, say, NSA has a quantum computer?
But for signatures we have time, right?

• Signatures provide authentication
• Cannot retroactively “decrypt” anything
• Stop accepting pre-quantum signatures once there is a quantum computer
• Will we know when, say, NSA has a quantum computer?
• May need to prepare devices today!
• Signatures are used for, e.g., software updates
• What if I cannot update anymore in 15 years?
  • What’s the lifetime of a car?
  • What’s the lifetime of smart-home appliances?
Plan for today

Lattice-based KEMs

• Intro lecture
• Programming exercise
Plan for today

Lattice-based KEMs

• Intro lecture
• Programming exercise

Hash-based signatures

• Intro lecture
• Programming exercise