The migration to post-quantum cryptography

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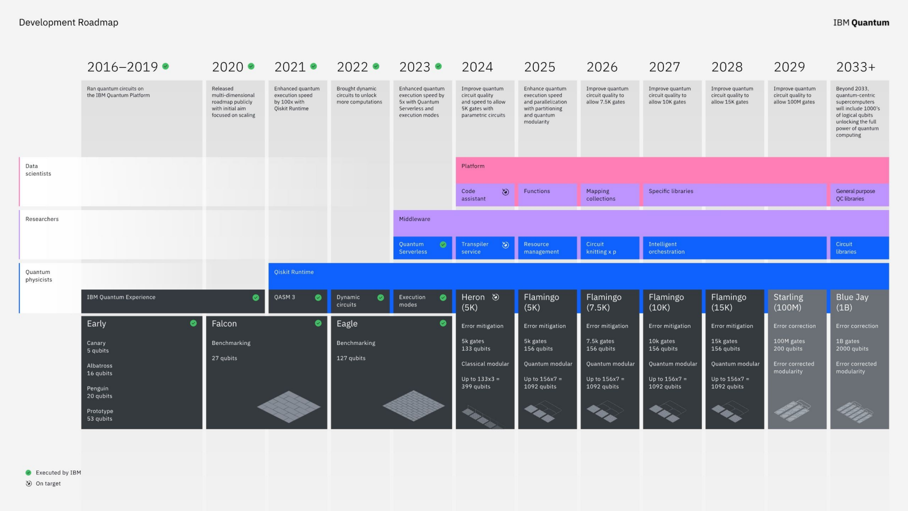
[A small demo]

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`

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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” (HNDL)

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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.

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“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

[Back to our demo]

So, all good? Is the world safe again?

A bit of history: the case of MD5

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Replacing MD5 was "easy"!

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- **HW resource planning:** Plan for increased computational and memory requirements
- **Protocol standards:** Updates needed wherever endpoints are not controlled by one party

Challenge 1: Performance

X25519 speed

- keygen: 28187 Skylake cycles
- shared: 87942 Skylake cycles

Kyber-768 speed

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- encaps: 53936 Skylake cycles
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X25519 sizes

- public key: 32 bytes

Kyber-768 sizes

- public key: 1184 bytes
- ciphertext: 1088 bytes

Challenge 2: A KEM is not DH!

Alice		Bob
$A \leftarrow g^a$		$B \leftarrow g^b$
	$\xrightarrow{\quad A \quad}$	
	$\xleftarrow{\quad B \quad}$	
$K \leftarrow B^a = (g^b)^a = g^{ab}$		$K \leftarrow A^b = (g^a)^b = g^{ab}$

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Challenge 2: A KEM is not DH!

Initiator		Responder
$(\mathsf{pk}, \mathsf{sk}) \leftarrow \mathsf{KEM.Gen}$		
	$\xrightarrow{\quad \mathsf{pk} \quad}$	
		$(\mathsf{ct}, K) \leftarrow \mathsf{KEM.Enc}(\mathsf{pk})$
	$\xleftarrow{\quad \mathsf{ct} \quad}$	
$K \leftarrow \mathsf{KEM.Dec}(\mathsf{ct}, \mathsf{sk})$		

Challenge 3: Bugs, bugs everywhere

Dilithium commit on Dec. 28, 2017

```diff
-        t  = buf[pos];
-        t |= (uint32_t)buf[pos + 1] << 8;
-        t |= (uint32_t)buf[pos + 2] << 16;
-        t &= 0xFFFFF;
+        t0  = buf[pos];
+        t0 |= (uint32_t)buf[pos + 1] << 8;
+        t0 |= (uint32_t)buf[pos + 2] << 16;
+        t0 &= 0xFFFFF;

-        t  = buf[pos + 2] >> 4;
-        t |= (uint32_t)buf[pos + 3] << 4;
-        t |= (uint32_t)buf[pos + 4] << 12;
+        t1  = buf[pos + 2] >> 4;
+        t1 |= (uint32_t)buf[pos + 3] << 4;
+        t1 |= (uint32_t)buf[pos + 4] << 12;
```

- Bug in Dilithium sampler
- Two consecutive coefficients are equal
- Allows key recovery
- Reported by Peter Pessl on Dec. 27, 2017

Challenge 3: Bugs, bugs everywhere

Questions about the range analysis of iNTT for "Faster Kyber and Dilithium on the Cortex-M4" #226

Closed **JunhaoHuang** opened this issue on Mar 3 · 4 comments

JunhaoHuang commented on Mar 3 • edited

Hi team, I am reading the Kyber code regarding the recent paper "Faster Kyber and Dilithium on the Cortex-M4", and I have a question about the matrix-vector product and Better Accumulation part regarding the *f_stack* version code.

I see that using the better accumulation technique in the f_speed version code, we can reduce each element of the output vector of matrix-vector product down to (-q,q). Since poly_invntt is normally used after the matrix-vector product, the range of the input vector of **poly_invntt** lies in (-q,q) in the *f_speed* version code. The **invntt** function works in this situation.

What I wonder is that in the *f_stack* version code, the **matacc** function actually uses the previous double basemul accumulation function, and it should produce the result vector with element in (-kq, kq), k is the security parameter of Kyber. For Kyber1024, the range of each polynomial element that **invntt** takes should be (-4q,4q). However, the **invntt** function is the same as the f_speed version code. The first four layers of the light butterflies in **invntt** involve some additions and subtractions without multiplication. Therefore, For Kyber1024 in the *f_stack* version code, two layers of addition/subtraction might overflow the int16_t. I wonder how you deal with this problem in the *f_stack* code and why does it still work?

Assignees

No one assigned

Labels

None yet

Projects

None yet

Milestone

No milestone

Development

No branches or pull requests

Challenge 3: Bugs, bugs everywhere

"...two layers of addition/subtraction might overflow the int16_t. I wonder how you deal with this problem in the f_stack code and why does it still work?"

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“. . . two layers of addition/subtraction might overflow the int16_t. I wonder how you deal with this problem in the f_stack code and why does it still work?”

“. . . On your question on why it still works, I believe that this is an edge case that does not get triggered by the testing scripts.”

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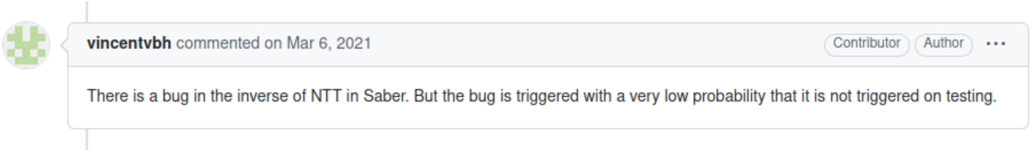

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vincentvbh commented on Mar 6, 2021 Contributor Author ...

There is a bug in the inverse of NTT in Saber. But the bug is triggered with a very low probability that it is not triggered on testing.

Both NTT bugs found by Yang, Liu, Shi, Hwang, Tsai, Wang, and Seiler (TCHES 2022/4)

Challenge 4: Implementation Security

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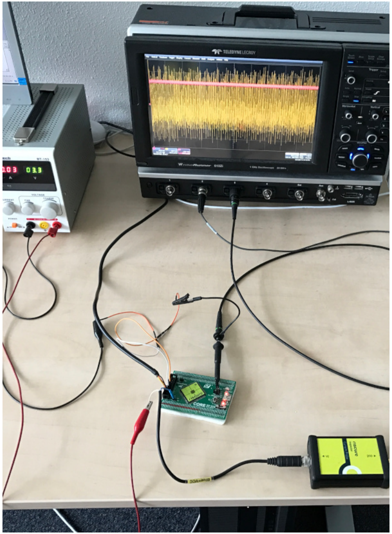

- Attackers see more than input/output:
  - Power consumption
  - Electromagnetic radiation
  - Timing
- Side-channel attacks:
  - Measure information
  - Use to obtain secret data

Challenge 4: Side-channel countermeasures

Hardware side-channels

- Require physical access to device
- Examples: Power, EM attacks
- Protection through dedicated countermeasures
- Typical slowdown of much more than 100%
- Progress, but no “conclusion”; we don’t know how to protect PQC!

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Software side-channels

- Leak through microarchitectural side-channels
- No physical access required, can run *remotely*
- Traditional countermeasure: **constant-time**
  - No branching on secrets
  - No memory access at secret location
  - No variable-time arithmetic on secrets

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Leaking binaries from constant-time code

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Advanced microarchitectural attacks

- Spectre (2018): leakage during *speculative execution*
- Hertzbleed (2022): Translate power leakage to timing leakage
- GoFetch (2024): Load instructions leak *data*
- ...

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  - Improve implementation security over time
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Broad consensus: PQC deployments today should be hybrid!

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Sizes

- PQC cryptographic objects are much bigger than for ECC
- X25519 PK: 32 B
- Additing 32 Bytes to 1KB makes almost no difference

Three approaches to “hybrididzation”

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Hybrid primitive

- + Low analysis effort (analyze *once*)
- + Close-to optimal performance
- +/- Cryptographically opinionated

We haven't even talked about signatures. . .

Same, same, but different. . .

- There is no HNDL attacks $\rightarrow$ migration less urgent for most systems
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  - secure boot on HW root of trust
- Performance even more challenging for Dilithium than for Kyber
- May be worth re-designing protocols to avoid signatures, e.g.,
  - KEMTLS (avoid handshake signatures in TLS)
  - Merkle-tree certificates for TLS

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Do these things in parallel!

Learn more

- NIST PQC website:
  https://csrc.nist.gov/Projects/Post-Quantum-Cryptography
- BSI recommendations:
  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
- EU migration roadmap:
  https://digital-strategy.ec.europa.eu/en/library/coordinated-implementation-roadmap-transition-post-quantum-cryptography
- NCCoE migration roadmap:
  https://www.nccoe.nist.gov/crypto-agility-considerations-migrating-post-quantum-cryptographic-algorithms
- MITRE/PQCC migration roadmap:
  https://pqcc.org/post-quantum-cryptography-migration-roadmap/
- PQCA software resources:
  https://pqca.org/