Radboud University

The transition to post-quantum cryptography

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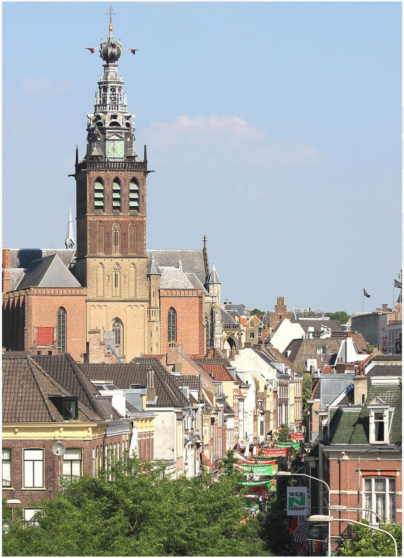
- Assistant professor at Radboud University
- Working on high-speed high-security crypto software
- Last time in Nancy: 2012 (?)



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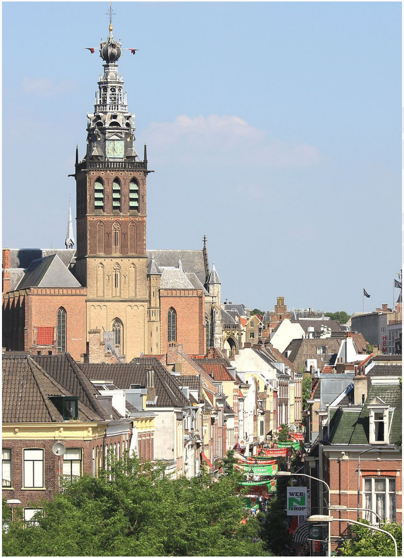

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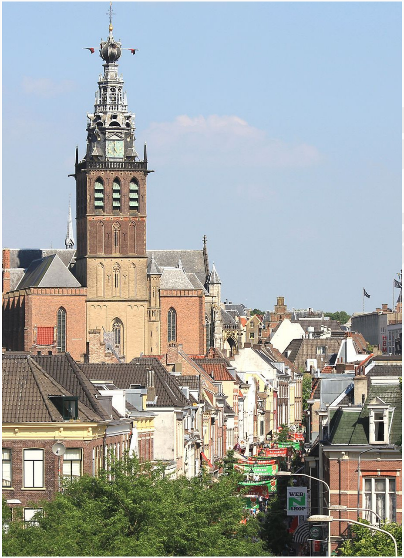
- This talk:
  - higher level
  - no assembly
  - most vague performance numbers I've ever used



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Symmetric crypto

- Block or stream cipher (e.g., AES, ChaCha20)
- Authenticator (e.g., HMAC, GMAC, Poly1305)
- Hash function (e.g., SHA-2, SHA-3)

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- Signatures (e.g., RSA, DSA, ECDSA, EdDSA)

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The asymmetric monoculture

- All widely deployed asymmetric crypto relies on
  - the **hardness of factoring**, or
  - the **hardness of (elliptic-curve) discrete logarithms**

. . . Shor, 1996

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.

Will there be quantum computers?

"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

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 competition

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.

“Key exchange”

- What is meant is **key encapsulation mechanisms** (KEMs)
  - $(pk, sk) \leftarrow \text{KeyGen}()$
  - $(c, k) \leftarrow \text{Encaps}(pk)$
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Status of the NIST competition

- In total 69 submissions accepted as "complete and proper"
- Several already broken
- 3 withdrawn

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- Can wait until NIST standardizes some algorithms in 5–7 years
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  - mediocre performance (designed pre-quantum, instantiated post-quantum)
  - Suboptimal security properties

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- Would generate a generation of rather poor protocols
  - mediocre performance (designed pre-quantum, instantiated post-quantum)
  - Suboptimal security properties
- Bad crypto is very hard to get rid of (think MD5)
- We probably have *one shot* to get this done properly
  - Systems *will* have to transition to PQ crypto
  - Let's work on getting the best out of this transition!
  - Requires interaction between cryptographers and systems designers

The starting point: ECC

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- Let's look at post-quantum candidates (at NIST security level 3)

PQ-KEMs, part 1: code-based

- Idea: Take error-correcting code for up to t errors
- Keep *decoding* algorithm secret
- Encryption: map message to code word, add t errors
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- "Classic McEliece" KEM NIST submission:
  - Encapsulation: $< 300\,000$ cycles
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  - Cipher text: 226 bytes
  - Public key: ≈ 1 MB
- Probably good choice for, e.g., GPG, but not for low-latency applications
- Possible solution: use QCMDPC codes (NIST candidate "BIKE")
- Less studied, less conservative, problems with CCA security

PQ-KEMs, part 2: lattice-based

- Typically based on (variants of) LWE
- Given uniform $\mathbf{A} \in \mathbb{Z}_q^{k \times \ell}$ and "noise distribution" χ
- Given samples $\mathbf{As} + \mathbf{e}$, with $\mathbf{e} \leftarrow \chi$, find $\mathbf{s}$

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- Structured lattices considered less conservative
- Many different design choices and tradeoffs

PQ-KEMs, part 3: SIKE

- Started as "supersingular-isogeny Diffie-Hellman" (SIDH), Jao, De Feo, 2011
- Given two elliptic curves E, E' from the same isogeny class
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- Secure SIDH (or SIKE) is **not** "analogous to the Diffie-Hellman key exchange"
- SIKE performance:
  - Keygen: $\approx$ 30 Mio cycles
  - Encaps/Decaps: $\approx$ 50 Mio cycles each
  - Public key/ciphertext: $<$ 600 bytes each

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- Can also construct signatures with reduction from $\mathcal{MQ}$
- Example: MQDSS
  - Signing $\approx$ 8.5 Mio cycles
  - Verification $\approx$ 5.8 Mio cycles
  - Signature: $\approx$ 40 KB
  - Public key: 72 bytes

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- As for KEMs, typically use structured lattices
- Example: Dilithium
  - Signing: $\approx$ 1.8 Mio cycles
  - Verification: $\approx$ 400 000 cycles
  - Public key: $\approx$ 1.5 KB
  - Signature: $\approx$ 2.7 KB

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- Example: SPHINCS
  - Signing: $\approx$ 52 Mio cycles
  - Verification: $\approx$ 1.5 Mio cycles
  - Signature: $\approx$ 40 KB
  - Public key is small
  - Up to 2^{50} signatures

Stateful signatures

- Hash-based signatures are already (almost) standardized
- XMSS standard draft submitted to IETF for conflict review
- Also highly parametrizable, for example:
  - Signing: $\approx$ 12.5 Mio cycles
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- **Start thinking systems with *stateful* signatures**

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- Can build AKE using CCA-secure KEMs only
- See the OPTLS proposal (Krawczyk, Wee, 2015)
- This is what systems like Signal, Noise already do
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… **for Signatures**

- First intuition: keygen can be slow
- Second look: not terribly slow
- Smartcard producers need to generate lots of keys
- Not a *huge* concern, RSA keygen is slow already today

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- Adam Langley: "2^{60} is fine"
- Obvious question: how about 2^{50}, 2^{40}, 2^{30}, ...?
- This is important to know for size/speed optimization

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  - are less robust (e.g., think key caching)
- **My intuition: only standardize/use CCA-secure KEMs**

We're going to miss DH

- Diffie-Hellman is extremely versatile:
- Can use it, for example, for **non-interactive key exchange (NIKE)**
  - Bob knows Alice' long-term public key A
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  - They can each compute $k = h(A, B, aB) = h(A, B, bA)$
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- **Extremely expensive** to instantiate post-quantum
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- **Conclusion: Design protocols that don't need NIKE**

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- This means that certificates are signed KEM public keys
- Use HSMs and smartcards for stateful, forward-secure signatures
- If impossible: fall back to slower, larger stateless signatures
- Carefully optimize hash-based signatures per application

Conclusion

- There are now 60+ concrete post-quantum schemes now
- There is software for all of those (which sometimes even works)
- Try them out, put them into systems, see what fails
- Start rethinking protocols and systems for a post-quantum world

Resources online

- Personal website:
  https://cryptojedi.org
- NIST PQC website:
  https://csrc.nist.gov/Projects/Post-Quantum-Cryptography
- PQC Lounge:
  https://www.safecrypto.eu/pqclounge/
- NIST mailing list:
  https://www.safecrypto.eu/pqclounge/