1
QUICK REMINDERS ON CRYPTO

CRYPTOGRAPHY GOALS

Ensure communication security over a public channel with adversaries

- Passive: The adversaries listen to the conversation (Eavesdropper)
- Active: They can write, alter, remove communications over the channel

What is the secret ingredient?

QUICK TIMELINE

- Artisanal Age: ($\sim$ 1900)
  - Caesar: Each letter is replaced by one 3 steps after
  - Generalized in basic permutation / substitution (Vigenere, Hill, ...)
- Mechanical Age: ($\sim$ 1900 $\rightarrow$ 1970)
  - Substitution and permutation are done by machines (Hagelin, Enigma (2nd WW))
- Paradoxical Age: (Since 1970)
  - Doing impossible things: Zero-Knowledge Proofs, Anonymous Authentication, Machine Learning on Encrypted Data

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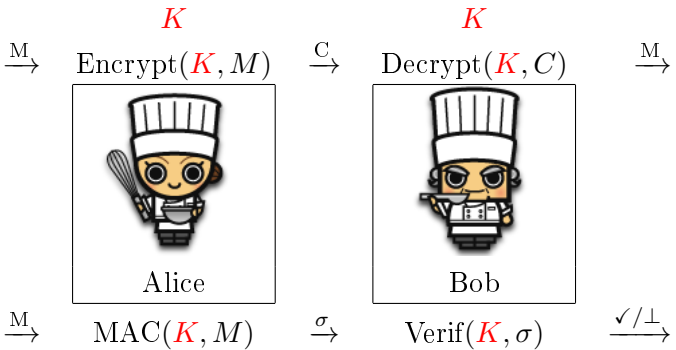
  - Post-Quantum Cryptography

SYMMETRIC CRYPTOGRAPHY

The key K used to encrypt / sign is the same used to decrypt / verify



Security (Enc): Without knowing K one cannot recover M. (DES, AES, ...)
Security (Auth): Without knowing K one cannot authenticate M.

ASYMMETRIC CRYPTOGRAPHY

There is a set of keys, a public key P_B accessible by everyone to encrypt, and a secret key K_B to decrypt possessed only by Bob.

$\xrightarrow{M}$ Encrypt(P_B, M) $\xrightarrow{C}$ Decrypt(K_B, C) $\xrightarrow{M}$

$\xrightarrow{M}$ Sign(K_A, M) $\xrightarrow{\sigma}$ Verif(P_A, σ) $\xrightarrow{\checkmark/\perp}$

Security (Enc): Without knowing K_B one cannot recover M even when knowing P_B. (RSA, ElGamal, ...)

Security (Auth): Without knowing K_A one cannot sign M even when knowing P_A.

PARAMETERS

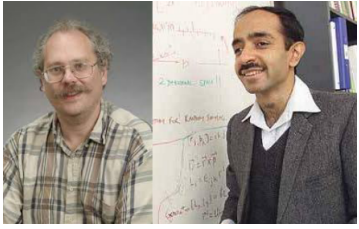
- With current computers, we consider that 2^{64} operations is within reach of an adversary.
- Birthday paradox says that 128 bits of security is de-facto the minimum requirement. (256, or even 512 are more and more recommended)
- For asymmetric cryptography, one may want at least 1536 bits for RSA, et 256 for Elliptic Curves.

2
THE QUANTUM MENACE

QUANTUM AGAINST CRYPTOGRAPHY

1994 Peter Shor proposed a quantum algorithm breaking discrete logarithm and factorisation assuming enough qubits.

1996 Grover proposed a quantum algorithm allowing to search unstructured sets of size N in $O(\sqrt{N})$



A BRIEF SUMMARY

	Symmetric	Asymmetric
Encryption	Grover	Shor
Authentication	Grover	Shor

Encryption: Save now, attack later
Signature: Need a live attack

A DANGER, NOT SO CLOSE

Applying Shor algorithm requires:

- a huge number of qubits
- even more quantum gates

Estimates show that for the 256 bits of security, we need **2330** qubits to break the discrete logarithm on elliptic curves, and **3072** to factor an RSA modulus.

Current best quantum computer claims... **256** qubits with some restriction.

3
A POSTQUANTUM WORLD

WHAT WOULD REMAIN AFTER THE QUANTUM TSUNAMI?

Cryptography based on isogenies?	Probably
Lattice-based / Code-based cryptography?	Quite likely
Multivariate cryptography?	Quite likely too
Hash-based cryptography?	Yes! (but no encryption)

NEW HYPOTHESES: CODES/LATTICES

Syndrome Decoding / Short Integer Solution

Given $\mathbf{A}$, $\mathbf{s}$ find a *small* $\mathbf{x}$ such that $\mathbf{Ax} = \mathbf{s}$

Learning With Error

Given $\mathbf{A}$, and $\mathbf{c}$, decide whether $\mathbf{c}$ is *close* to the span of $\mathbf{A}$. (ie $\mathbf{c} = \mathbf{As} + \mathbf{e}$)

Warning Depending on the underlying ring/field, the noise sampling, the metric used, this can go very poorly

NEW HYPOTHESES, SAME TECHNIQUES: ISOGENIES

Random walks on graph

$$\begin{array}{ccc} E & \xrightarrow{\phi_1} & E_1 \\ \downarrow \phi_2 & & \downarrow \phi_2 \\ E_2 & \xrightarrow{\phi_1} & E_{12} \end{array}$$

Computation Supersingular Diffie-Hellman

Given E, E_1, E_2, find E_{12}.

Warning The main problem (SIDH) was broken this summer (few seconds on a laptop). But CSIDH using group action remains safe.

The MQ Problem

Given

- A finite field of q elements $\mathbb{F}_q$;
- m quadratic polynomials $p_1, \ldots, p_m \in \mathbb{F}_q[X_1, \ldots, X_n]$ in n variables.

Find a solution $(x_1, \ldots, x_n) \in \mathbb{F}_q^n$ to the system of equations $p_i(X_1, \ldots, X_n) = 0$.

Warning Finding the right balance between efficiency and security is complex, and lead to attacks.

ENTER THE NIST PQ COMPETITION

- International Call in 2016
- 69 proposals at Round 1 (16 Fr)
- Round 2, only 26 remains
  - 9 Signatures (**Lattices, MV, Hash**) (3 Fr)
  - 17 KEM (**Lattices, Codes, Isogenies**) (6 Fr)
- Round 3, 7 finalists, 8 alternates:
  - 3 (+3) Signatures (**Lattices, MV, Hash**) (3 + 1 Fr)
  - 4 (+5) KEM (**Lattices, Codes, Isogenies**) (2 + 2 Fr)
- Standardisation of 3 Signatures, and 1 KEM all **Lattices** (2,1 Fr)
  - Round 4, for 4 KEM (**Codes, Isogenies**) (2 Fr) For October'22, then Summer'23?
  - New call for other kind of signatures For June'23

Pros: Many research papers, new attacks, tested in the wild (TLS 1.3...)

Cons: A lot of noise, and non scientific disruptions

RESULTS OF NIST

A PostQuantum world

Standardized* (Lattices)

E/σ **CRYSTAL-Kyber/ Dilithium**: ENS Lyon, ARM, NXP, CWI, RUB, SRI, IBM, Waterloo, Radboud

σ **FALCON**: Rennes 1, Thales, Brown, IBM, NCC, OnBoard Security

σ **SPHINCS$^+$**: Taurus, RUB, KUL, Graz, Genua, Eindhoven, G, Infineon, Cisco, USD, Radboud, Cloudflare

4th Round, Encryption

- **Classic McEliece**: Inria, RHUL, RUB, Sinica, Okinawa, ETHZ, Eindhoven, G, FAU, MPI, Yale, PQSolutions
- **HQC**: Rennes, Worldline, Enac, U.Toulon, U.Limoges, U.Bordeaux, Polytechnique, G, FAU
- **BIKE**: Rennes, Wordline, Enac, U.Limoges, Supaero, Inria, Bordeaux, Polytechnique, UoW, Intel, Haifa, RUB, G, FAU
- **SIKE**: IBM, Infosec Global, Louisian Tech, Linkedin, NRC, TI, Radboud, Toronto, Waterloo, FAU, A,M

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- **BIKE**: Rennes, Wordline, Enac, U.Limoges, Supaero, Inria, Bordeaux, Polytechnique, UoW, Intel, Haifa, RUB, G, FAU

? **SIKE**: IBM, Infosec Global, Louisian Tech, Linkedin, NRC, TI, Radboud, Toronto, Waterloo, FAU, A,M

AND NOW?

Should we switch to PQC?

ANSSI, and other agencies are warning that switching to PQC only is probably risky, an hybrid design (**Vanilla+PQC**) seems safer and wiser.
Schemes that were in the final stages were broken on classical computers. It is still **too early** to trust them completely

Classical **hybrid** design would be only slightly less efficient than PQC only (Increase by 10%). It is also an interesting path of research to explore this hybrid aspect and see if there are further optimizations possible between the standards/finalists and classical schemes.

NIST and NSA have been very elliptical about this...

WRAPPING UP

Quantum Computers!
Will annihilate classical cryptography...
some day

4 main kind of hypotheses exist
Lattice and codes are the safest choice for now, as they have been extensively studied

Encryption
Can still be meaningful in 20 years, so we need to update today

France
Is well represented, 25% of the submission, 75% of the standards/finalists