Introduction to post-quantum cryptography I

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Cryptography

- Motivation #1: Communication channels are spying on our data.
- Motivation #2: Communication channels are modifying our data.

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Sender
“Alice”

Untrustworthy network
“Eve”

Receiver
“Bob”

- Literal meaning of cryptography: “secret writing”.
- Achieves various security goals by secretly transforming messages.

Secret-key encryption

- Prerequisite: Alice and Bob share a secret key .
- Prerequisite: Eve doesn't know .
- Alice and Bob exchange any number of messages.
- Security goal #1: **Confidentiality** despite Eve's espionage.

Secret-key authenticated encryption

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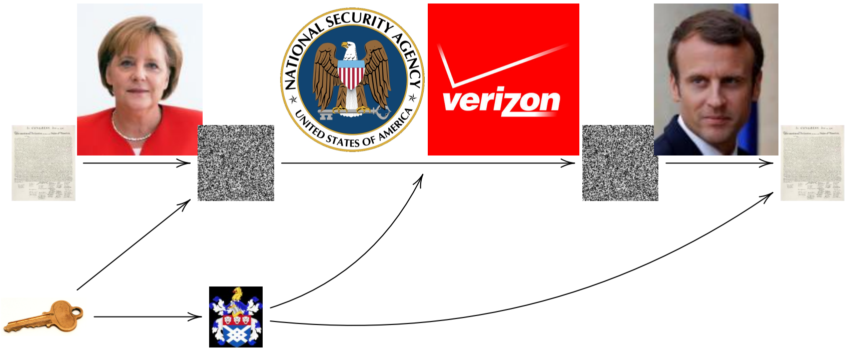
Public-key signatures



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- Prerequisite: Eve doesn't know . Everyone knows .
- Alice publishes any number of messages.
- Security goal: Integrity.

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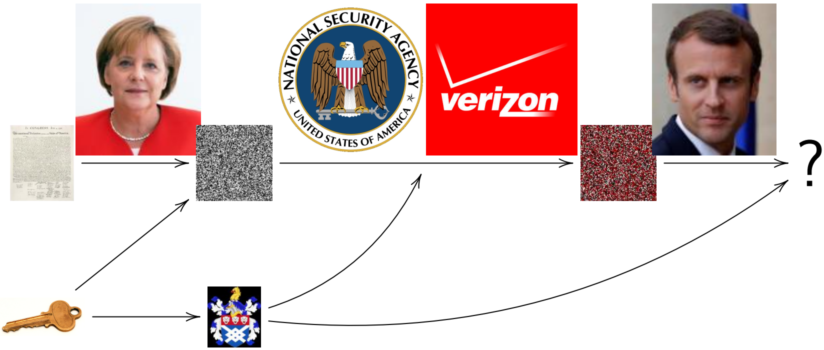

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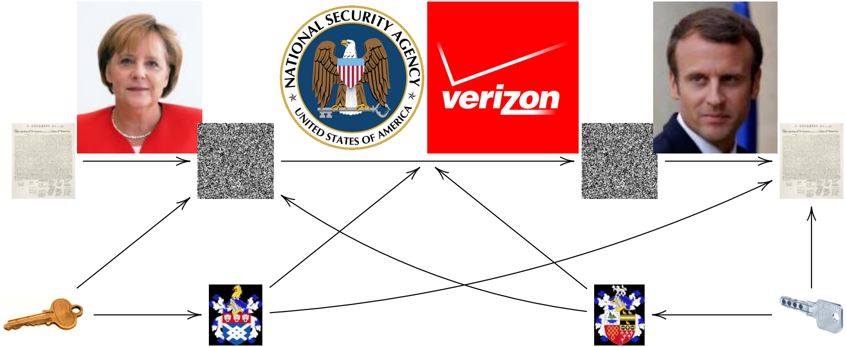
Public-key authenticated encryption ("DH" data flow)



- Prerequisite: Alice has a secret key  and public key .
- Prerequisite: Bob has a secret key  and public key .
- Alice and Bob exchange any number of messages.
- Security goal #1: Confidentiality.
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Cryptographic tools

Many factors influence the security and privacy of data:

- Secure storage, physical security; access control.
- Protection against alteration of data
  $\Rightarrow$ public-key signatures, message-authentication codes.
- Protection of sensitive content against reading
  $\Rightarrow$ encryption.

Many more security goals studied in cryptography

- Protecting against denial of service.
- Stopping traffic analysis.
- Securely tallying votes.
- Searching in and computing on encrypted data.
- ...

Cryptanalysis

- Cryptanalysis is the study of security of cryptosystems.
- Breaking a system can mean that the hardness assumption was not hard or that it just was not as hard as previously assumed.
- Public cryptanalysis is ultimately constructive – ensure that secure systems get used, not insecure ones.
- Weakened crypto ultimately backfires – attacks in 2018 because of crypto wars in the 90s.
- Good arsenal of general approaches to cryptanalysis. There are some automated tools.
- This area is constantly under development; researchers revisit systems continuously.

Security assumptions

- Hardness assumptions at the basis of all public-key and essentially all symmetric-key systems result from (failed) attempts at breaking systems. Security proofs are built only on top of those assumptions.
- A solid symmetric system is required to be as strong as exhaustive key search.
- For public-key systems the best attacks are faster than exhaustive key search. Parameters are chosen to ensure that the best attack is infeasible.

Key size recommendations

	Parameter	Legacy	Future System Use Near Term	Future System Use Long Term
Symmetric Key Size	k	80	128	256
Hash Function Output Size	m	160	256	512
MAC Output Size*	m	80	128	256
RSA Problem	$\ell(n) \geq$	1024	3072	15360
Finite Field DLP	$\ell(p^n) \geq$	1024	3072	15360
	$\ell(p), \ell(q) \geq$	160	256	512
ECDLP	$\ell(q) \geq$	160	256	512
Pairing	$\ell(p^{k \cdot n}) \geq$	1024	6144	15360
	$\ell(p), \ell(q) \geq$	160	256	512

- Source: ECRYPT-CSA "Algorithms, Key Size and Protocols Report" (2018).
- These recommendations take into account attacks known today.
- Use extrapolations to larger problem sizes.
- Attacker power typically limited to 2^{128} operations (less for legacy).
- More to come on long-term security ...

Summary: current state of the art

- Currently used crypto (check the lock icon in your browser) starts with RSA, Diffie-Hellman (DH) in finite fields, or elliptic-curve Diffie-Hellman (ECDH).
- Older standards are RSA or elliptic curves from NIST (or Brainpool), e.g. NIST P256 or ECDSA.
- Internet currently moving over to Curve25519 (Bernstein) and Ed25519 (Bernstein, Duif, Lange, Schwabe, and Yang).
- For symmetric crypto TLS (the protocol behind https) uses AES or ChaCha20 and some MAC, e.g. AES-GCM or ChaCha20-Poly1305. High-end devices have support for AES-GCM, smaller ones do better with ChaCha20-Poly1305.
- Security is getting better. Some obstacles: bugs; untrustworthy hardware;

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- Security is getting better. Some obstacles: bugs; untrustworthy hardware; let alone anti-security measures such as laws restricting encryption in Australia, China, Iran, Russia, UK.

Algorithms for Quantum Computation: Discrete Logarithms and Factoring

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AT&T Bell Labs
Room 2D-149
600 Mountain Ave.
Murray Hill, NJ 07974, USA

Abstract

A computer is generally considered to be a universal computational device; i.e., it is believed able to simulate any physical computational device with a cost in computation time of at most a polynomial factor. It is not clear whether this is still true when quantum mechanics is taken into consideration. Several researchers, starting with David Deutsch, have developed models for quantum mechanical computers and have investigated their computational properties. This paper gives Las Vegas algorithms for finding discrete logarithms and factoring integers on a quantum computer that take a number of steps which is polynomial in the input size, e.g., the number of digits of the integer to be factored. These two problems are generally considered hard on a classical computer and have been used as the basis of several proposed cryptosystems. (We thus give the first examples of quantum cryptanalysis.)

[1, 2]. Although he did not ask whether quantum mechanics conferred extra power to computation, he did show that a Turing machine could be simulated by the reversible unitary evolution of a quantum process, which is a necessary prerequisite for quantum computation. Deutsch [9, 10] was the first to give an explicit model of quantum computation. He defined both quantum Turing machines and quantum circuits and investigated some of their properties.

The next part of this paper discusses how quantum computation relates to classical complexity classes. We will thus first give a brief intuitive discussion of complexity classes for those readers who do not have this background. There are generally two resources which limit the ability of computers to solve large problems: time and space (i.e., memory). The field of analysis of algorithms considers the asymptotic demands that algorithms make for these resources as a function of the problem size. Theoretical computer scientists generally classify algorithms as efficient when the number of steps of the algorithms grows as a polynomial in the size of the input. The class of prob-

Effects of large universal quantum computers

- Massive research effort. Tons of progress summarized in, e.g., https://en.wikipedia.org/wiki/Timeline_of_quantum_computing.
- Mark Ketchen, IBM Research, 2012, on quantum computing: “We’re actually doing things that are making us think like, ‘hey this isn’t 50 years off, this is maybe just 10 years off, or 15 years off.’ It’s within reach.”
- Fast-forward to 2022, or 2027. Universal quantum computers exist.
- Shor’s algorithm solves in polynomial time:
  - Integer factorization. RSA is dead.
  - The discrete-logarithm problem in finite fields. DSA is dead.
  - The discrete-logarithm problem on elliptic curves. ECDHE is dead.
- This breaks all current public-key cryptography on the Internet!

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- This breaks all current public-key cryptography on the Internet!
- Also, Grover's algorithm speeds up brute-force searches.
- Example: Only 2^{64} quantum operations to break AES-128;
  2^{128} quantum operations to break AES-256.

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Post-quantum cryptography

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Sender
"Alice"

"Eve"
with a quantum computer

Receiver
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- Literal meaning of cryptography: "secret writing".
- Security goal #1: **Confidentiality** despite Eve's espionage.
- Security goal #2: **Integrity**, i.e., recognizing Eve's sabotage.
- Post-quantum cryptography adds to the model that Eve has a quantum computer.

Post-quantum cryptography:
Cryptography designed
under the assumption that
the **attacker** (not the user!)
has a large quantum computer.

National Academy of Sciences (US) report on quantum computing

Don't panic. "Key Finding 1: Given the current state of quantum computing and recent rates of progress, it is highly unexpected that a quantum computer that can compromise RSA 2048 or comparable discrete logarithm-based public key cryptosystems will be built within the next decade."

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Panic. "Key Finding 10: Even if a quantum computer that can decrypt current cryptographic ciphers is more than a decade off, the hazard of such a machine is high enough—and the time frame for transitioning to a new security protocol is sufficiently long and uncertain—that prioritization of the development, standardization, and deployment of post-quantum cryptography is critical for minimizing the chance of a potential security and privacy disaster."

High urgency for long-term confidentiality

- Today's encrypted communication is being stored by attackers and will be decrypted years later with quantum computers. Danger for human-rights workers, medical records, journalists, security research, legal proceedings, state secrets, . . .

- Signature schemes can be replaced once a quantum computer is built – but there will not be a public announcement

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- Signature schemes can be replaced once a quantum computer is built – but there will not be a public announcement ... and an important function of signatures is to protect operating system upgrades.
- Protect your upgrades *now* with post-quantum signatures.

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PQCRYPTO
ICT-645622

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PQCRYPTO
ICT-645622

- PQCRYPTO was an EU project in H2020, running 2015 – 2018.
- PQCRYPTO designed a portfolio of high-security post-quantum public-key systems, and improved the speed of these systems, adapting to the different performance challenges of mobile devices, the cloud, and the Internet.

Initial recommendations of long-term secure post-quantum systems

Daniel Augot, Lejla Batina, Daniel J. Bernstein, Joppe Bos,
Johannes Buchmann, Wouter Castryck, Orr Dunkelman,
Tim Güneysu, Shay Gueron, Andreas Hülsing,
Tanja Lange, Mohamed Saied Emam Mohamed,
Christian Rechberger, Peter Schwabe, Nicolas Sendrier,
Frederik Vercauteren, Bo-Yin Yang

Initial recommendations

- **Symmetric encryption** Thoroughly analyzed, 256-bit keys:
  - AES-256
  - Salsa20 with a 256-bit key

  Evaluating: Serpent-256, ...
- **Symmetric authentication** Information-theoretic MACs:
  - GCM using a 96-bit nonce and a 128-bit authenticator
  - Poly1305
- **Public-key encryption** McEliece with binary Goppa codes:
  - length $n = 6960$, dimension $k = 5413$, $t = 119$ errors

  Evaluating: QC-MDPC, Stehlé-Steinfeld NTRU, ...
- **Public-key signatures** Hash-based (minimal assumptions):
  - XMSS with any of the parameters specified in CFRG draft
  - SPHINCS-256

  Evaluating: HFEv-, ...

Post-quantum secret-key authenticated encryption

$$m \xrightarrow[k]{} c \longrightarrow c \xrightarrow[k]{} m$$

- Very easy solutions if secret key k is long uniform random string:
  - "One-time pad" for encryption.
  - "Wegman–Carter MAC" for authentication, e.g., Poly1305.
- AES-256: Standardized method to expand 256-bit k into string indistinguishable from long k.
- AES introduced in 1998 by Daemen and Rijmen. Security analyzed in papers by dozens of cryptanalysts.
- Alternative: ChaCha20 (or Salsa20) well analyzed stream cipher with 256-bit key; in TLS 1.3.
- No credible threat from quantum algorithms. Grover costs 2^{128}.

Systems expected to survive

- Code-based encryption and signatures.
- Hash-based signatures.
- Isogeny-based encryption.
- Lattice-based encryption and signatures.
- Multivariate-quadratic encryption and signatures.
- Symmetric encryption and authentication.

This list is based on the best known attacks (as always).

These are categories of mathematical problems;
individual systems may be totally insecure if the problem is not used correctly.

We have a good understanding of what a quantum computer can do,
but new systems need more analysis.

Short summaries

- Code-based encryption: short ciphertexts and large public keys. Very long and stable security history.
- Hash-based signatures: very solid security and small public keys. Require only a secure hash function (hard to find second preimages). Very long and stable security history.
- Isogeny-based encryption: new kid on the block, promising short keys and ciphertexts and non-interactive key exchange. Systems rely on hardness of finding isogenies between elliptic curves over finite fields.
- Lattice-based encryption and signatures: possibility for balanced sizes. Security relies on finding short vectors in some (typically special) lattice.
- Multivariate-quadratic signatures: short signatures and large public keys. Systems rely on hardness of solving systems of multi-variate equations over finite fields.

Standardization efforts

I E T F Datatracker Groups Documents Meetings Other User

```
Internet Research Task Force (IRTF)                          A. Huelsing
Request for Comments: 8391                                 TU Eindhoven
Category: Informational                                         D. Butin
ISSN: 2070-1721                                             TU Darmstadt
                                                               S. Gazdag
                                                              genua GmbH
                                                             J. Rijneveld
                                                      Radboud University
                                                             A. Mohaisen
                                          University of Central Florida
                                                                May 2018

                  XMSS: eXtended Merkle Signature Scheme
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- NIST (National Institute for Standards and Technology) asked for submissions to post-quantum project. Ongoing efforts to analyze, implement, select; final results expected in 3-5 years.
- ETSI QSC: several whitepapers.
- ISO: working on whitepaper.
- OASIS: KMIP (key management) standard with PQC.
- ANSI and IEEE have standardized NTRU (not for PQC parameters).

Deployment issues & solutions

- Different recommendations for rollout:
    - Use most efficient systems with ECC or RSA, to ease usage and gain familiarity.
    - Use most conservative systems (possibly with ECC), to ensure that data really remains secure.

  These recommendations match different risk scenarios.
- Protocol integration and implementation problems:
    - Key sizes or message sizes are larger for post-quantum systems, but IPv6 guarantees only delivery of $\leq$ 1280-byte packets.
    - Google experimented with larger keys and noticed delays and dropped connections.
    - Long-term keys require extra care (reaction attacks).
- Some libraries exist, but mostly for experiments, not production quality.
- Google and Cloudflare very recently announced some experiments of including post-quantum systems into TLS.

Links

- NIST PQC competition https://csrc.nist.gov/Projects/Post-Quantum-Cryptography
- PQCRYPTO EU project https://pqcrypto.eu.org:
  - Expert recommendations.
  - Free software libraries (libpqcrypto, pqm4, pqhw).
  - Lots of reports, scientific papers, (overview) presentations.
- PQCRYPTO summer school 2017 with 21 lectures on video + slides + exercises. https://2017.pqcrypto.org/school:
- PQCrypto 2019 conference.
- PQCrypto 2018 conference.
- PQCrypto 2017 conference.
- PQCrypto 2016 with slides and videos from lectures + school.
- https://pqcrypto.org: Survey site by Danniel J. Bernstein & TL
  - Many pointers: e.g., PQCrypto conference series.
  - Bibliography for 4 major PQC systems.