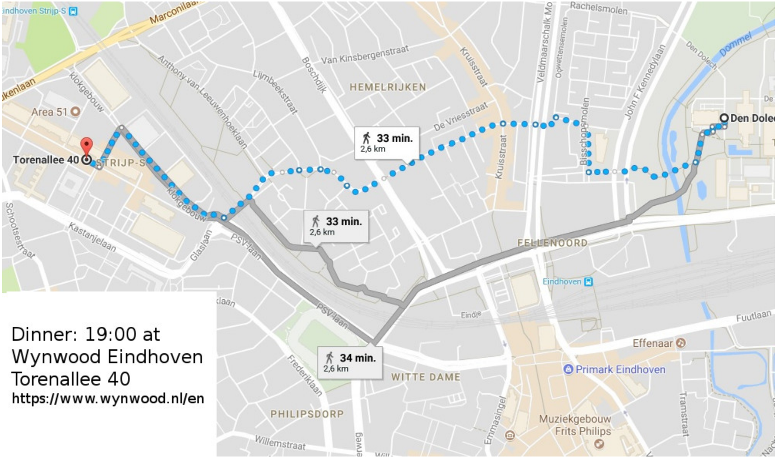
Executive PQC School

- 2 days of taks.
- Lunches in this building.
- Dinner starts at 19:00 at Restaurant Wynwood (bit of a walk or take public transportation).



Introduction to post-quantum cryptography

Tanja Lange

Technische Universiteit Eindhoven

22 June 2017

Executive School on Post-Quantum Cryptography

Cryptographic applications in daily life

- Mobile phones connecting to cell towers.
- Credit cards, EC-cards, access codes for banks.
- Electronic passports; soon ID cards.
- Internet commerce, online tax declarations, webmail.
- Facebook, Gmail, WhatsApp, iMessage on iPhone.
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- Encrypted file system on iPhone: see Apple vs. FBI.

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Snowden in Reddit AmA

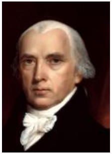
> *Arguing that you don't care about the right to privacy because you have nothing to hide is no different than saying you don't care about free speech because you have nothing to say.*

Cryptography

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

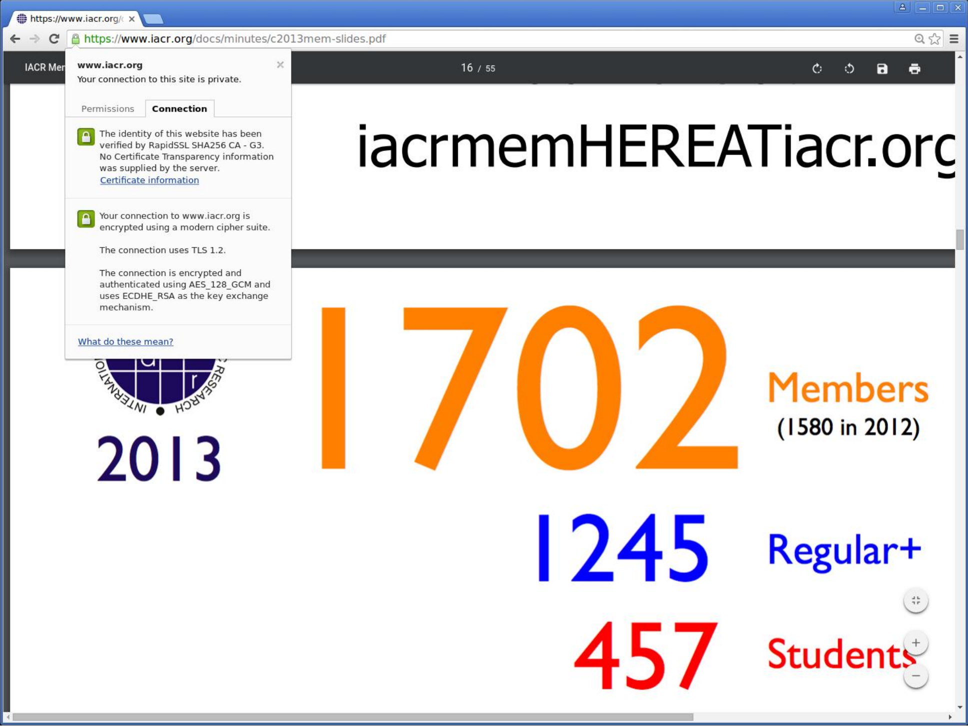
Sender
"Alice"

$\longrightarrow$ Untrustworthy network
"Eve" $\longrightarrow$



Receiver
"Bob"

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


https://www.iacr.org/
https://www.iacr.org/docs/minutes/c2013mem-slides.pdf
IACR Mem
16 / 55
www.iacr.org
Your connection to this site is private.
Permissions
Connection
The identity of this website has been verified by RapidSSL SHA256 CA - G3. No Certificate Transparency information was supplied by the server.
Certificate information
Your connection to www.iacr.org is encrypted using a modern cipher suite.
The connection uses TLS 1.2.
The connection is encrypted and authenticated using AES_128_GCM and uses ECDHE_RSA as the key exchange mechanism.
What do these mean?
iacrmemHEREATiacr.org
2013
1702
Members
(1580 in 2012)
1245
Regular+
457
Students


https://www.iacr.org/
https://www.iacr.org/docs/minutes/c2013mem-slides.pdf
IACR Mer
16 /
www.iacr.org
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Permissions
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What do these mean?
iacrm

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.

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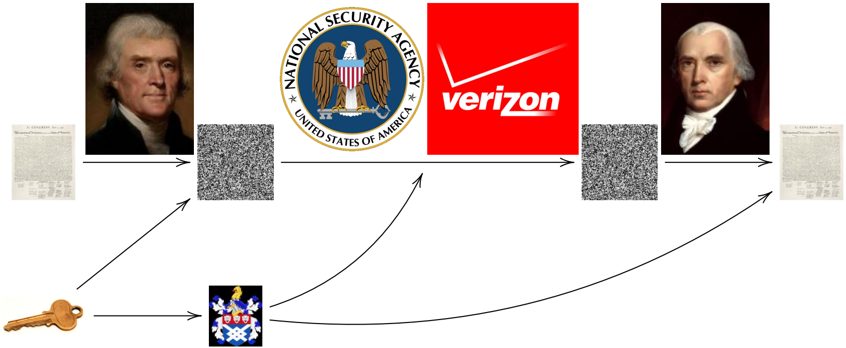

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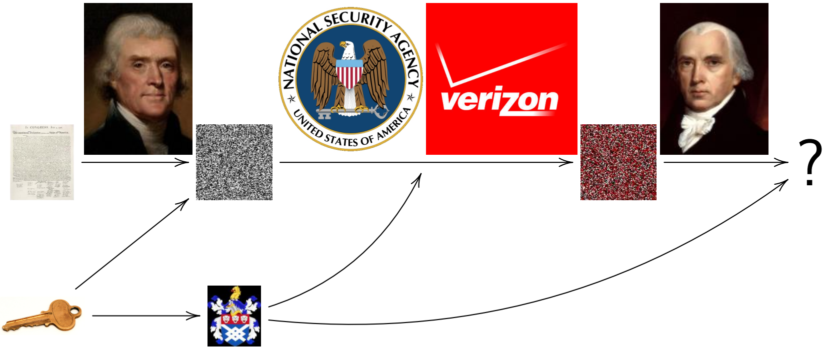

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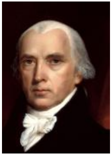
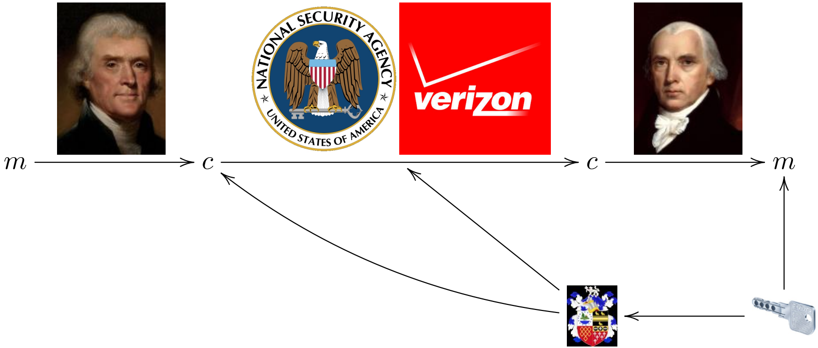
 

$$\begin{tikzcd}
m \arrow[r] & m, s \arrow[rr] & {} & m, s \arrow[r] & m \\
k \arrow[r] \arrow[ur] & K \arrow[ur, bend right] \arrow[urrr, bend right] & & &
\end{tikzcd}$$

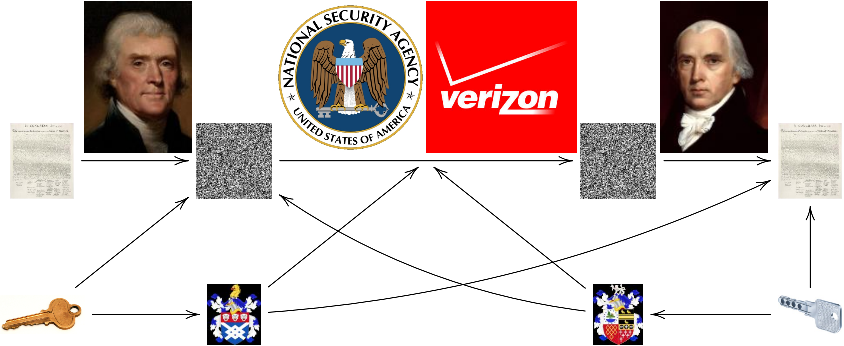
Secret key $k =$ , public key $K =$ .

Public-key encryption



- Alice uses Bob's public key $K =$  to encrypt.
- Bob uses his secret key $k =$  to decrypt.

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



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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.

Currently used crypto (check the lock icon in your browser) starts with RSA, Diffie-Hellman (DH) in finite fields, or elliptic curve DH, followed by AES or ChaCha20.

Internet currently moving over to Curve25519 (Bernstein) and Ed25519 (Bernstein, Duif, Lange, Schwabe, and Yang).

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Security is getting better. Some obstacles: bugs; untrustworthy hardware;let alone anti-security measures such as backdoors.

Algorithms for Quantum Computation: Discrete Logarithms and Factoring

Peter W. Shor
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

[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


D:wave
D:wave
D:wave

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- Can't store stable qubits.
- Can't perform basic qubit operations.
- Can't run Shor's algorithm.
- Can't run other quantum algorithms we care about.

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- Can't perform basic qubit operations.
- Can't run Shor's algorithm.
- Can't run other quantum algorithms we care about.
- Hasn't managed to find any computation justifying its price.
- Hasn't managed to find any computation justifying 1% of its price.

... but universal quantum computers are coming ...

- Massive research effort. Tons of progress summarized in, e.g., https://en.wikipedia.org/wiki/Timeline_of_quantum_computing.

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- 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."
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  - The discrete-logarithm problem in finite fields. DSA is dead.
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- 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.

Physical cryptography: a return to the dark ages

- Imagine a lockable-briefcase salesman proposing a "locked-briefcase Internet" using "provably secure locked-briefcase cryptography":
  - Alice puts secret information into a lockable briefcase.
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  - We should not dignify this proposal with a response.

Security advantages of algorithmic cryptography

- Keep secrets heavily shielded inside authorized computers.
- Reduce trust in third parties:
  - Reduce reliance on closed-source software and hardware.
  - Increase comprehensiveness of audits.
  - Increase comprehensiveness of formal verification.
  - Design systems to be secure even if **algorithm and public keys are public**.
    Critical example: **signed** software updates.
- Understand security as thoroughly as possible:
  - Publish comprehensive specifications.
  - Build large research community with clear security goals.
  - Publicly document attack efforts.
  - Require systems to convincingly survive many years of analysis.

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- PQCrypto 2008, PQCrypto 2010, PQCrypto 2011, PQCrypto 2013.
- 2014 EU publishes H2020 call including post-quantum crypto as topic.
- ETSI working group on "Quantum-safe" crypto.
- PQCrypto 2014.
- April 2015 NIST hosts first workshop on post-quantum cryptography
- August 2015 NSA wakes up

NSA announcements

August 11, 2015

> *IAD recognizes that there will be a move, in the not distant future, to a quantum resistant algorithm suite.*

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Post-quantum becoming mainstream

- PQCrypto 2016: 22–26 Feb in Fukuoka, Japan, $>$ 200 people

- NIST is calling for post-quantum proposals; submissions due Nov 2017.

Confidence-inspiring crypto takes time to build

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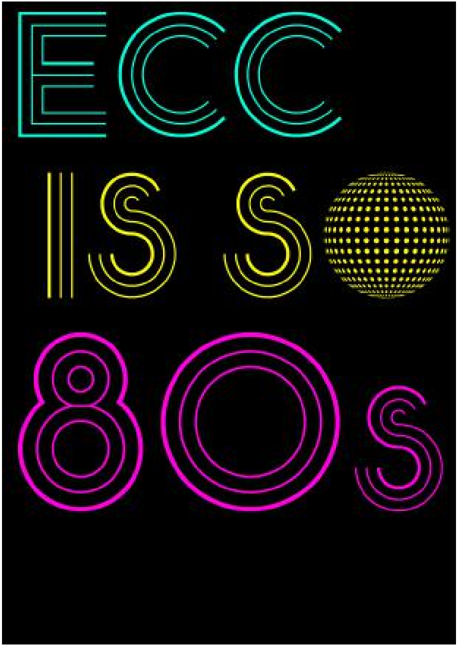
- Example: ECC introduced **1985**; big advantages over RSA.
  Robust ECC started to take over the Internet in **2015**.
- Can't wait for quantum computers before finding a solution!


ECC
IS SO
80s

Even higher 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.

Standardize now? Standardize later?

- Standardize now!
  - Rolling out crypto takes long time.
  - Standards are important for adoption (?)
  - Need to be up & running when quantum computers come.

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  - Please wait for the research results, will be much better!
- But what about users who rely on long-term secrecy of today's communication?
- Recommend now, standardize later.
- Recommend very conservative systems now; users who care will accept performance issues and gladly update to faster/smaller options later.
- But: standardization takes lots of time, so start standardization processes now.

Urgency of post-quantum recommendations

- All currently used public-key systems on the Internet are broken by quantum computers.
- Today's encrypted communication can be (and is being!) stored by attackers and can be decrypted later with quantum computer – think of medical records, legal proceedings, and state secrets.
- Post-quantum secure cryptosystems exist (to the best of our knowledge) but are under-researched – we can recommend secure systems now, but they are big and slow

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PQCRYPTO
ICT-645622

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- PQCRYPTO is an EU project in H2020, running 2015 – 2018.
- PQCRYPTO is designing a portfolio of high-security post-quantum public-key systems, and will improve 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

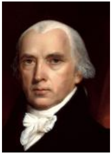
  Evaluating: HFEv-, ...

Systems expected to survive

- Code-based crypto, see talks by Nicolas Sendrier
- Hash-based signatures, see talks by Andreas Hülsing
- Isogeny-based crypto: new kid on the block, promising short keys and key exchange without communication (static-static) as possibility; needs more reserach on security.
- Lattice-based crypto, see talks by Thijs Laarhoven & Peter Schwabe
- Multivariate crypto, see talks by Bo-Yin Yang
- Symmetric crypto.

Maybe some more, maybe some less.

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.
- 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.
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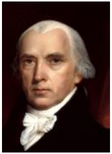

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Further resources

- https://pqcrypto.org: Our survey site.
  - Many pointers: e.g., PQCrypto conference series.
  - Bibliography for 4 major PQC systemss.
- PQCrypto 2016 with slides and videos from lectures (incl. winter school)
- PQCrypto 2017 amd two schools (with slides and soon videos)
- https://pqcrypto.eu.org: PQCRYPTO EU project.
  - Expert recommendations.
  - Free software libraries. (Coming soon)
  - More benchmarking to compare cryptosystems. (Coming soon)
  - 2017: workshop and spring/summer school.
- https://twitter.com/pqc_eu: PQCRYPTO Twitter feed.
  - Get used to post-quantum cryptosystems.
  - Improve; implement; integrate into real-world systems.