Code-Based Cryptography

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Cryptography

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

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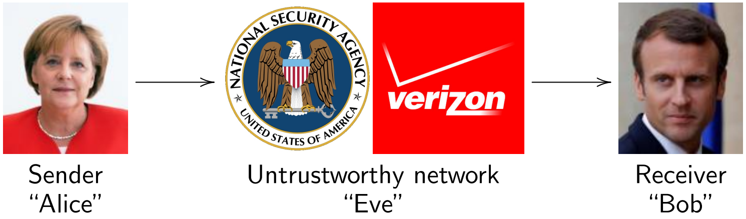

- Literal meaning of cryptography: “secret writing”.
- Security goal #1: **Confidentiality** despite Eve’s espionage.
- Security goal #2: **Integrity**, i.e., recognizing Eve’s sabotage.

Symmetric cryptography

- Alice and Bob share a secret key.
- They use this key for encryption:
  both parties can encrypt and decrypt.
  - Stream ciphers encrypt streams of bits: Salsa20, ChaCha20, (RC4), ...
  - Block ciphers encrypt messages of fixed length: AES, Serpent, (DES), ...
    Longer messages are encrypted using modes of operations to chain the blocks: CBC, CTR, ...
- They use this key for authentication and integrity protection: each party is convinced that a message comes from the respective other party and that it has not been modified.
  - Message authentication codes (MACs) add such a checksum: GCM, HMAC, Poly1305, ...
- Typically a combination is needed, e.g., AES-GCM, ChaCha20-Poly1305, ...
- Hash functions map strings of arbitrary length to strings of fixed length. Even though there is no secret they are typically considered part of symmetric cryptography.

Public key cryptography

- Alice a pair of keys: her public key and her private key.
- The key parts are linked by some mathematical function so that computing the private key from the public key should be hard.
- Anybody can see and use Alice's public key (Bob, Charlie, Eve, ...)
- Only Alice knows her private key.
- Anybody can use Alice's public key to encrypt to her; only she can decrypt (using the private key).
  - Messages satisfy some mathematical properties, e.g., integer $< n$. point on an elliptic curve, ...
  - Examples are RSA, Diffie-Hellman in finite fields, ECDH, ...
- Alice uses her private key to sign a message; anybody can verify the signature using her public key.
  - Signatures ensure authenticity and integrity: anybody is convinced that the message comes from Alice and that it has not been modified.
  - Examples are RSA, DSA, ECDSA.

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

- Hardness assumptions at the basis of all public-key and essentially all symmetric-key systems result from (failed) attack attempts. 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 known today is infeasible.
- Attacker power limited to 2^{128} operations (2^{80} for legacy).
- Source: ECRYPT-CSA "Algorithms, Key Size and Protocols Report"

Algorithms for Quantum Computation: Discrete Logarithms and Factoring

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AT&T Bell Labs
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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-

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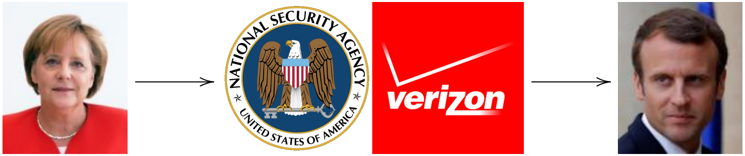

Sender
"Alice"

Untrustworthy network
"Eve"

Receiver
"Bob"

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Post-quantum cryptography

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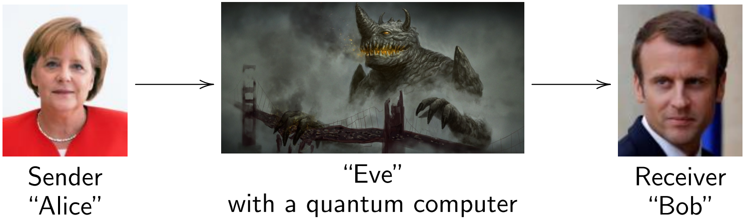

- Literal meaning of cryptography: "secret writing".
- Security goal #1: **Confidentiality** despite Eve's espionage.
- Security goal #2: **Integrity**, i.e., recognizing Eve's sabotage.
- Post-quantum cryptography adds to the model that Eve has a quantum computer.

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

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. DH is dead.
  - The discrete-logarithm problem on elliptic curves. ECC 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.

National Academy of Sciences (US)

4 December 2018: 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."

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.

Short summaries

- Code-based encryption: short ciphertexts and large public keys. More in a moment.
- Hash-based signatures: very solid security and small public keys. Require only a secure hash function (hard to find second preimages).
- 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.

Code-based encryption

- 1971 Goppa: Fast decoders for many matrices H.
- 1978 McEliece: Use Goppa codes for public-key crypto.
  - Original parameters designed for 2^{64} security.
  - 2008 Bernstein–Lange–Peters: broken in $\approx 2^{60}$ cycles.
  - Easily scale up for higher security.
- 1986 Niederreiter: Simplified and smaller version of McEliece.
- 1962 Prange: simple attack idea guiding sizes in 1978 McEliece.
  The McEliece system (with later key-size optimizations)
  uses $(c_0 + o(1))\lambda^2(\lg \lambda)^2$-bit keys as $\lambda \to \infty$
  to achieve 2^λ security against Prange's attack.
  Here $c_0 \approx 0.7418860694$.

Security analysis

Some papers studying algorithms for attackers:
1962 Prange; 1981 Clark–Cain, crediting Omura; 1988 Lee–Brickell; 1988 Leon; 1989 Krouk; 1989 Stern; 1989 Dumer; 1990 Coffey–Goodman; 1990 van Tilburg; 1991 Dumer; 1991 Coffey–Goodman–Farrell; 1993 Chabanne–Courteau; 1993 Chabaud; 1994 van Tilburg; 1994 Canteaut–Chabanne; 1998 Canteaut–Chabaud; 1998 Canteaut–Sendrier; 2008 Bernstein–Lange–Peters; 2009 Bernstein–Lange–Peters–van Tilborg; 2009 Bernstein (**post-quantum**); 2009 Finiasz–Sendrier; 2010 Bernstein–Lange–Peters; 2011 May–Meurer–Thomae; 2012 Becker–Joux–May–Meurer; 2013 Hamdaoui–Sendrier; 2015 May–Ozerov; 2016 Canto Torres–Sendrier; 2017 Kachigar–Tillich (**post-quantum**); 2017 Both–May; 2018 Both–May; 2018 Kirshanova (**post-quantum**).

Consequence of security analysis

- The McEliece system (with later key-size optimizations) uses $(c_0 + o(1))\lambda^2(\lg \lambda)^2$-bit keys as $\lambda \to \infty$ to achieve 2^λ security against all these attacks.

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- 256 KB public key for 2^{146} pre-quantum security.
- 512 KB public key for 2^{187} pre-quantum security.
- 1024 KB public key for 2^{263} pre-quantum security.

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- 256 KB public key for 2^{146} pre-quantum security.
- 512 KB public key for 2^{187} pre-quantum security.
- 1024 KB public key for 2^{263} pre-quantum security.
- Post-quantum (Grover): below 2^{263}, above 2^{131}.

The McEliece cryptosystem I

- Let C be a length-n binary Goppa code Γ of dimension k with minimum distance $2t+1$ where $t \approx (n-k)/\log_2(n)$; original parameters (1978) $n = 1024$, $k = 524$, $t = 50$.
- The McEliece secret key consists of a generator matrix G for Γ, an efficient t-error correcting decoding algorithm for Γ; an $n \times n$ permutation matrix P and a nonsingular $k \times k$ matrix S.
- n, k, t are public; but Γ, P, S are randomly generated secrets.
- The McEliece public key is the $k \times n$ matrix $G' = SGP$.

The McEliece cryptosystem II

- Encrypt: Compute $\mathbf{m}G'$ and add a random error vector $\mathbf{e}$ of weight t and length n. Send $\mathbf{y} = \mathbf{m}G' + \mathbf{e}$.
- Decrypt: Compute $\mathbf{y}P^{-1} = \mathbf{m}G'P^{-1} + \mathbf{e}P^{-1} = (\mathbf{m}S)G + \mathbf{e}P^{-1}$. This works because $\mathbf{e}P^{-1}$ has the same weight as $\mathbf{e}$

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  This works because $\mathbf{e}P^{-1}$ has the same weight as $\mathbf{e}$
  because P is a permutation matrix.
  Use fast decoding to find $\mathbf{m}S$ and $\mathbf{m}$.
- Attacker is faced with decoding $\mathbf{y}$ to nearest codeword $\mathbf{m}G'$ in the code generated by G'.
  This is general decoding if G' does not expose any structure.
- Wrote attack software against original McEliece parameters, decoding 50 errors in a $[1024, 524]$ code.
- Attack on a single computer with a 2.4GHz Intel Core 2 Quad Q6600 CPU would need, on average, 1400 days (2^{58} CPU cycles) to complete the attack.
- Running the software on 200 such computers would reduce the average time to one week.

The Niederreiter cryptosystem I

Developed in 1986 by Harald Niederreiter as a variant of the McEliece cryptosystem. This is the schoolbook version.

- Use parity-check matrix H instead of generator matrix.
- Use $n \times n$ permutation matrix P, $n-k \times n-k$ invertible matrix S.
- Public Key: a scrambled parity-check matrix $K = SHP \in \mathbf{F}_2^{(n-k)\times n}$.
- Encryption: The plaintext $\mathbf{e}$ is an n-bit vector of weight t.
  The ciphertext $\mathbf{s}$ is the $(n-k)$-bit vector
  $$\mathbf{s} = K\mathbf{e}.$$
- Decryption: Find a n-bit vector $\mathbf{e}$ with $\mathrm{wt}(\mathbf{e}) = t$ such that $\mathbf{s} = K\mathbf{e}$.
- The passive attacker is facing a t-error correcting problem for the public key, which seems to be random.

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- Public Key: a scrambled parity-check matrix $K = SHP$.
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- Decryption using secret key: Compute

$$\begin{aligned} S^{-1}\mathbf{s} &= S^{-1}K\mathbf{e} = S^{-1}(SHP)\mathbf{e} \\ &= H(P\mathbf{e}) \end{aligned}$$

  and observe that $\mathrm{wt}(P\mathbf{e}) = t$, because P permutes.
- Use efficient syndrome decoder for H to find $\mathbf{e}' = P\mathbf{e}$ and thus $\mathbf{e} = P^{-1}\mathbf{e}'$.

Note on codes

- McEliece proposed to use binary Goppa codes.
  These are still used today.
- Niederreiter described his scheme using Reed-Solomon codes.
  These were broken in 1992 by Sidelnikov and Chestakov.
- More corpses on the way: concatenated codes, Reed-Muller codes, several Algebraic Geometry (AG) codes, Gabidulin codes, several LDPC codes, cyclic codes.
- Some other constructions look OK (for now).
  NIST competition has several entries on QCMDPC and rank-metric codes.

How to hide nice code?

- Let $q = 2^m$. A binary Goppa code is defined by
  - a list $L = (a_1, \ldots, a_n)$ of n distinct elements in $\mathbf{F}_q$, called the support.
  - a square-free polynomial $g(x) \in \mathbf{F}_q[x]$ of degree t such that $g(a) \neq 0$ for all $a \in L$. $g(x)$ is called the Goppa polynomial.
  - E.g. choose $g(x)$ irreducible over $\mathbf{F}_q$.

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  - E.g. choose $g(x)$ irreducible over $\mathbf{F}_q$.
- Use secret $g(x)$ and secret permutation of the a_i, this corresponds to secret permutation of the n positions; this replaces P.
- Secret key is polynomial g and support $L = (a_1, \dots, a_n)$. Can generate both by expanding a small seed.
- Use systematic form $K = (K'|I)$ for key;
  - This implicitly applies S.
  - No need to remember S because decoding does not use H.
  - Public key size decreased to $(n - k) \times k$.

Do not use the schoolbook versions!

Sloppy Alice attacks! 1998 Verheul, Doumen, van Tilborg

- Assume that the decoding algorithm decodes up to t errors, i. e. it decodes $\mathbf{y} = \mathbf{c} + \mathbf{e}$ to $\mathbf{c}$ if $\mathrm{wt}(\mathbf{e}) \leq t$.
- Eve intercepts ciphertext $\mathbf{y} = \mathbf{m}G' + \mathbf{e}$.
  Eve poses as Alice towards Bob and sends him tweaks of $\mathbf{y}$.
  She uses Bob's reactions (success of failure to decrypt) to recover $\mathbf{m}$.
- Assume $\mathrm{wt}(\mathbf{e}) = t$. (Else flip more bits till Bob fails).
- Eve sends $\mathbf{y}_i = \mathbf{y} + \mathbf{e}_i$ for $\mathbf{e}_i$ the i-th unit vector.
  If Bob returns error, position i in $\mathbf{e}$ is 0 (so the number of errors has increased to $t + 1$ and Bob fails).
  Else position i in $\mathbf{e}$ is 1.
- After k steps Eve knows the first k positions of $\mathbf{m}G'$ without error.
  Invert the $k \times k$ submatrix of G' to get $\mathbf{m}$

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- After k steps Eve knows the first k positions of $\mathbf{m}G'$ without error.
  Invert the $k \times k$ submatrix of G' to get $\mathbf{m}$ assuming it is invertible.
- Proper attack: figure out invertible submatrix of G' at beginning; recover matching k coordinates.
- This attack has Eve send Bob variations of the same ciphertext; so Bob will think that Alice is sloppy.

Towards non-schoolbook version

- Attack also works on Niederreiter version:

Towards non-schoolbook version

- Attack also works on Niederreiter version:
  Bitflip cooresponds to sending $\mathbf{s}_i = \mathbf{s} + K_i$,
  where K_i is the i-th column of K.
- More involved but doable (for McEliece and Niederreiter) if decryption requires exactly t errors.
- Fix by using CCA2 transformation (e.g. Fujisaki-Okamoto transform) or (easier) KEM/DEM version:
  pick random $\mathbf{e}$ of weight t, use hash($\mathbf{e}$) as secret key to encrypt and authenticate (for McEliece or Niederreiter).
- Can prove security under the assumption that McEliece/Niederreiter are One-Way Encryption (OWE) schemes.

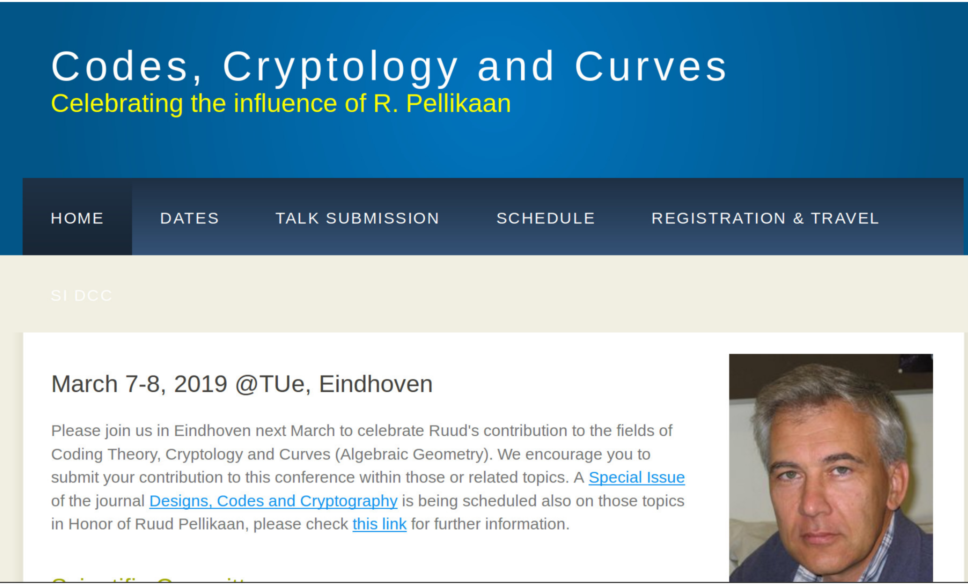
Classic McEliece highlights

- Security asymptotics unchanged by 40 years of cryptanalysis.
- Short ciphertexts.
- Efficient and straightforward conversion of OW-CPA PKE into IND-CCA2 KEM.
- Constant-time software implementations.
- FPGA implementation of full cryptosystem.
- Open-source (public domain) implementations.
- No patents.

Metric	**mceliece6960119**	**mceliece8192128**
Public-key size	1047319 bytes	1357824 bytes
Secret-key size	13908 bytes	14080 bytes
Ciphertext size	226 bytes	240 bytes
Key-generation time	1108833108 cycles	1173074192 cycles
Encapsulation time	153940 cycles	188520 cycles
Decapsulation time	318088 cycles	343756 cycles

See `https://classic.mceliece.org` for more details.

Conference advertisement



Codes, Cryptology and Curves

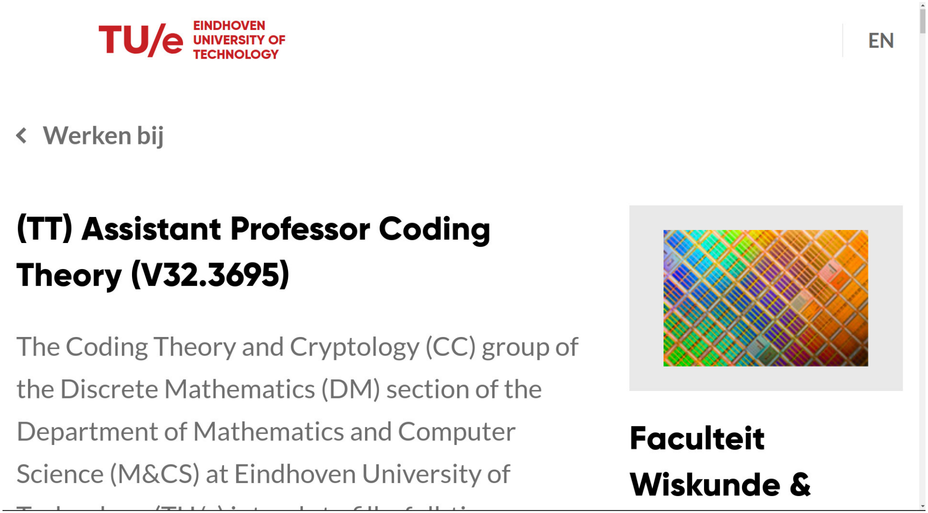
Celebrating the influence of R. Pellikaan

March 7-8, 2019 @TUe, Eindhoven

Please join us in Eindhoven next March to celebrate Ruud's contribution to the fields of Coding Theory, Cryptology and Curves (Algebraic Geometry). We encourage you to submit your contribution to this conference within those or related topics. A Special Issue of the journal Designs, Codes and Cryptography is being scheduled also on those topics in Honor of Ruud Pellikaan, please check this link for further information.

http://www.singacom.uva.es/~edgar/CCC/index.html

We're hiring!



TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY

EN

‹ Werken bij

(TT) Assistant Professor Coding Theory (V32.3695)

The Coding Theory and Cryptology (CC) group of the Discrete Mathematics (DM) section of the Department of Mathematics and Computer Science (M&CS) at Eindhoven University of

Faculteit Wiskunde &

https://jobs.tue.nl/nl/vacature/tt-assistant-professor-coding-theory-449061.html

Links and more upcoming events

- 18 & 19 May 7th Code-Based Cryptography Workshop
- 1 & 2 July 2019: Executive summer school on post-quantum cryptography in Eindhoven.
- `https://pqcrypto.eu.org`: PQCRYPTO EU project.
  - Expert recommendations.
  - Free software libraries (libpqcrypto, pqm4, pqhw).
  - Lots of reports, scientific papers, (overview) presentations.
- `https://2017.pqcrypto.org/school`: PQCRYPTO summer school with 21 lectures on video + slides + exercises.
- `https://2017.pqcrypto.org/exec`: Executive school (12 lectures), less math, more overview. So far slides, soon videos.
- PQCrypto 2018 & PQCrypto 2017 conferences.
- PQCrypto 2016 with slides and videos from lectures + school.
- `https://pqcrypto.org`: Survey site by D.J. Bernstein and me.
  - Many pointers: e.g., PQCrypto conference series.
  - Bibliography for 4 major PQC systems.
- `https://csrc.nist.gov/projects/post-quantum-cryptography/round-1-submissions`: NIST PQC competition.