Post-quantum cryptography

Daniel J. Bernstein

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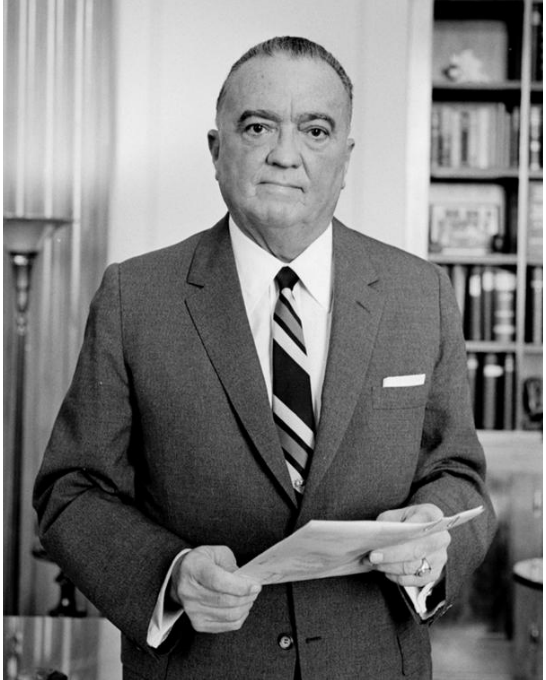

Wikipedia: “Hoover became a controversial figure as evidence of his secretive abuses of power began to surface. He was found to have exceeded the jurisdiction of the FBI, and to have used the FBI to harass political dissenters and activists, to amass secret files on political leaders, and to collect evidence using illegal methods. Hoover consequently amassed a great deal of power and was in a position to intimidate and threaten others, including sitting presidents of the United States.”

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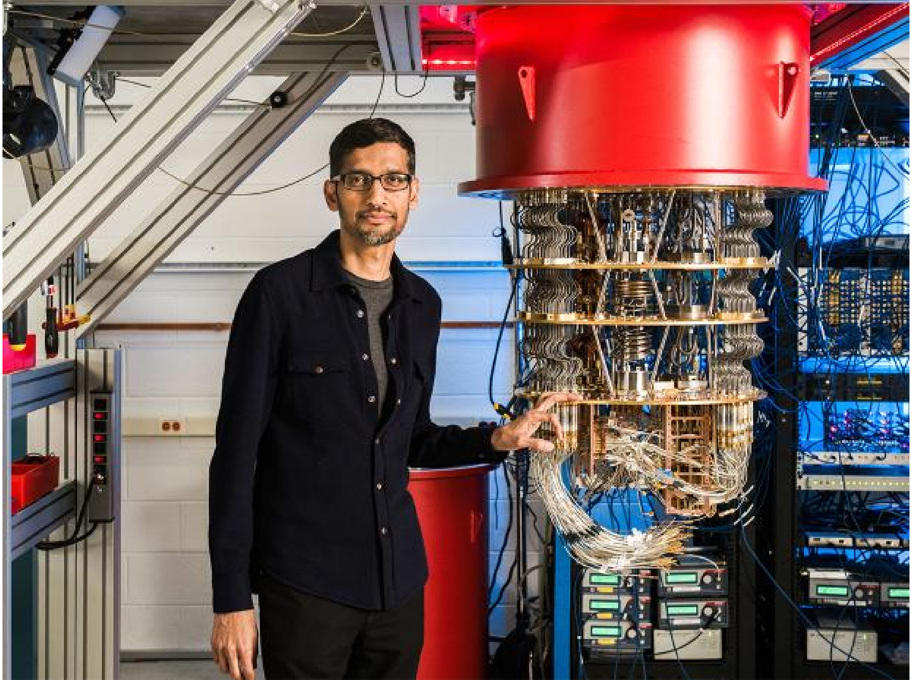
Thought experiment: Start from 2016 election results. Switch 5353+11375+22147 R voters to D in MI+WI+PA. $\Rightarrow$ Clinton wins. (Of course there were many other influences on election results.)



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The goals of cryptography

(Col. Carrington tells me he has sent you the first

volume of the federalist, and adds the 2d. by this conveyance.

mentioned to you that publication

I believe I never have yet 942. 1709. 770. 1234. 698. 802. 193. 310. It

was undertaken last fall by Jay Hamilton and myself

1293. 1054. 475. 640. 293. 139. 1461. 227. 1247. 770. 487. 1004. 872. 951. 440

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1461. 812. 491. 942. 546. 1302. 227. 1247. 1619. 1898. 1179. 812. 1091. 1727.

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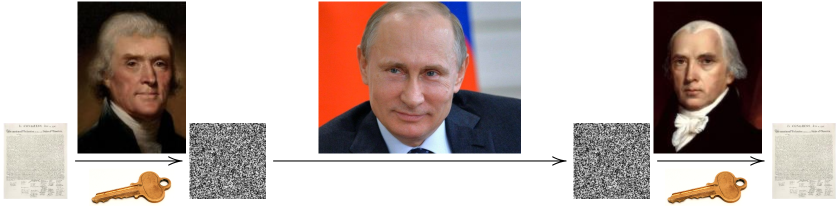
Secret-key encryption



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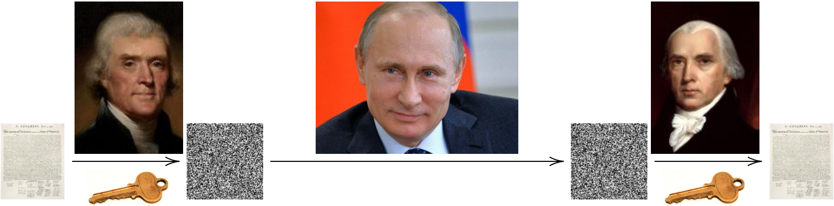
Prerequisite: Vladimir doesn't know .
Thomas and James exchange any number of messages.
Security goal #1: **Confidentiality** despite Vladimir's espionage.

Secret-key authenticated encryption



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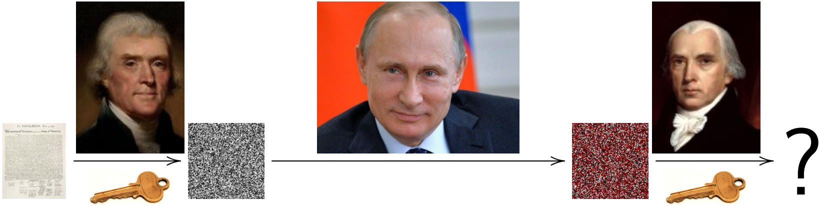

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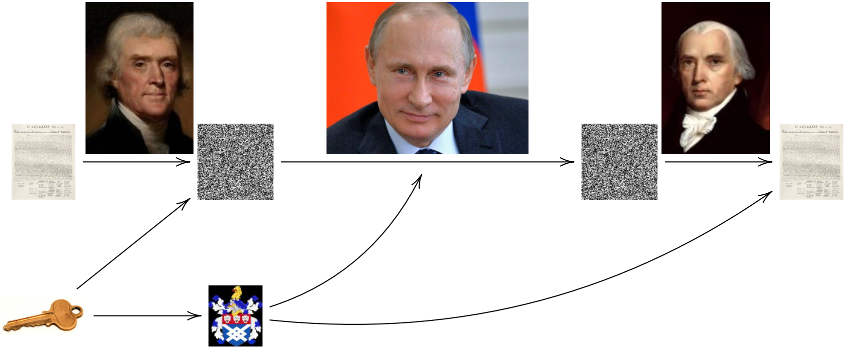

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Thomas publishes any number of messages.

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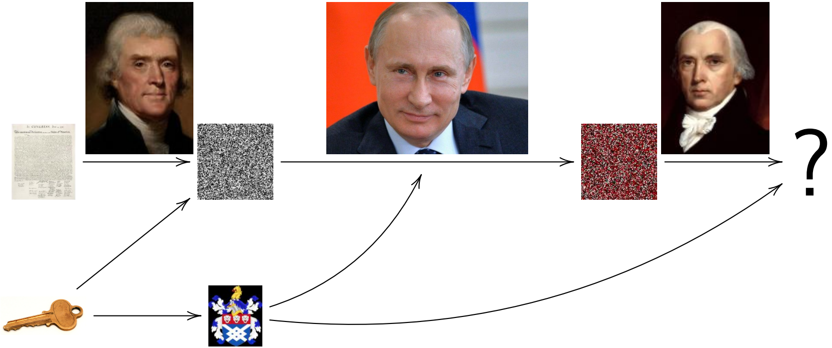

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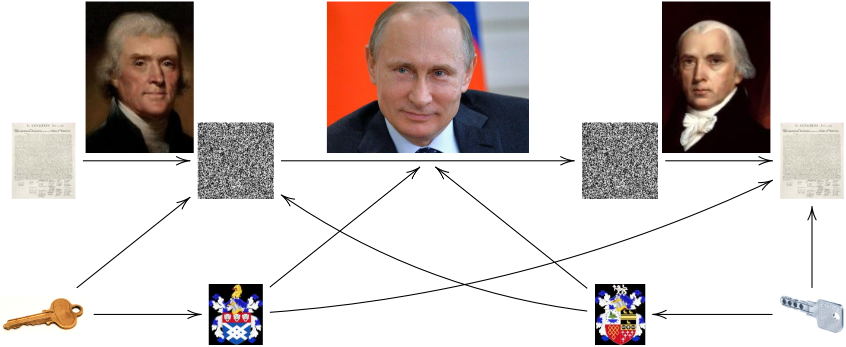
Public-key authenticated encryption (“DH” data flow)



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Cryptographers study many more security goals

Protecting against denial of service; stopping traffic analysis; securely tallying votes; searching encrypted data; much more.

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Assuming quantum attacks become cheap enough:

- Attackers forge messages if we don't change our systems.
- Attackers read messages if we don't change our systems.
- Attackers read older messages no matter what we do.

How cryptographers try to reach the goals

Many stages of research from design to deployment

Define the goals

Explore space of cryptosystems

Study algorithms for the attackers

Focus on secure cryptosystems

Study algorithms for the users

Study implementations on real hardware

Study side-channel attacks, fault attacks, etc.

Focus on secure, reliable implementations

Focus on implementations meeting performance requirements

Integrate securely into real-world applications

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Warning: waterfall data flow, undesirable.

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Public key is secretly generated with "binary Goppa code" structure that allows efficient decoding: $C \mapsto As, e$.

One-wayness (“OW-CPA” $=$ “OW-Passive”)

Fundamental security question:
Given random public key A and ciphertext $As + e$ for random s, e,
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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 $c_0 \approx 0.7418860694$.

Is the McEliece system really one-way?

25 subsequent papers studying one-wayness of McEliece system:
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 Finiasz–Sendrier.
2011 Bernstein–Lange–Peters. 2011 May–Meurer–Thomae.
2012 Becker–Joux–May–Meurer. 2013 Hamdaoui–Sendrier.
2015 May–Ozerov. 2016 Canto Torres–Sendrier.

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The attack papers have had an effect on the $o(1)$ terms,
and have slightly changed results for specific λ.
Exact analysis and optimization: harder than asymptotics.
Example of current work: count # quantum gates in algorithms.

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Are other security systems in better shape? — No. Even worse.

Binary Goppa codes (1970)

Parameters: $q \in \{8, 16, 32, \ldots\}$;
$w \in \{2, 3, \ldots, \lfloor (q-1)/\lg q \rfloor\}$; $n \in \{w \lg q + 1, \ldots, q-1, q\}$.

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McEliece uses random matrix A whose image is this code.

Niederreiter key compression (1986)

Generator matrix for code Γ of length n and dimension k:
$n \times k$ matrix G with $\Gamma = G \cdot \mathbf{F}_2^k$.

McEliece public key: G times random $k \times k$ invertible matrix.

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Pr $\approx$29% that systematic form exists. Security loss: $<$2 bits.

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If so, attacker can efficiently find s, e given A and $As + e$: compute $H(As + e) = He$; find e; compute s from As.

Performance concerns have led to much more work

Algorithms and software and hardware for McEliece users: e.g.,

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- Lattice-based cryptography.

The claimed maturity of lattice attacks

Case study: SVP, the most famous lattice problem.

2006 Silverman: "Lattices, SVP and CVP, have been intensively studied for more than 100 years, both as intrinsic mathematical problems and for applications in pure and applied mathematics, physics and cryptography."

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Best SVP algorithms known by 2000:
time $2^{\Theta(N \log N)}$ for almost all dimension-N lattices
(assuming reasonable input lengths, various reasonable heuristics).

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Lattice crypto: more attack avenues; even less understanding.

Is post-quantum crypto moving quickly enough?

1994: Shor's algorithm.

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2014: EU solicits grant proposals in post-quantum crypto.

2014: ETSI starts working group on "Quantum-safe" crypto.

2015.04: NIST hosts workshop on post-quantum cryptography.

2015.08: NSA wakes up.

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PQCrypto 2016: >200 people

PQCrypto 2018: 350 people

Rewinding to 2016 . . .

More reactions by government agencies:

- NSA posts another statement.
- NCSC UK posts statement on the threat to cryptography and statement on quantum key distribution.
- NCSC NL posts statement.
- After public input, NIST calls for submissions of public-key systems to "Post-Quantum Cryptography Standardization Project". Deadline 2017.11.

2017: Submissions to the NIST competition

21 December 2017: NIST posts 69 submissions from 260 people.

BIG QUAKE. BIKE. CFPKM. Classic McEliece. Compact LWE. CRYSTALS-DILITHIUM. CRYSTALS-KYBER. DAGS. Ding Key Exchange. DME. DRS. DualModeMS. Edon-K. EMBLEM and R.EMBLEM. FALCON. FrodoKEM. GeMSS. Giophantus. Gravity-SPHINCS. Guess Again. Gui. HILA5. HiMQ-3. HK17. HQC. KINDI. LAC. LAKE. LEDAkem. LEDApkc. Lepton. LIMA. Lizard. LOCKER. LOTUS. LUOV. McNie. Mersenne-756839. MQDSS. NewHope. NTRUEncrypt. pqNTRUSign. NTRU-HRSS-KEM. NTRU Prime. NTS-KEM. Odd Manhattan. OKCN/AKCN/CNKE. Ouroboros-R. Picnic. pqRSA encryption. pqRSA signature. pqsigRM. QC-MDPC KEM. qTESLA. RaCoSS. Rainbow. Ramstake. RankSign. RLCE-KEM. Round2. RQC. RVB. SABER. SIKE. SPHINCS+. SRTPI. Three Bears. Titanium. WalnutDSA.

Some submissions are broken within days

By end of 2017: 8 out of 69 submissions attacked.

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Some less secure than claimed; some smashed; some attack scripts.

Do cryptographers have any idea what they're doing?

By end of 2018: 22 out of 69 submissions attacked.

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Do cryptographers have any idea what they're doing?

By end of 2019: 30 out of 69 submissions attacked.

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An attempt to explain the situation

People often categorize submissions. Examples of categories:

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

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Lattice security estimates are so imprecise that nobody is sure whether the remaining submissions are damaged by a 2019 paper solving a lattice problem "more than a million times faster".

Call for merged submissions

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“Submissions should only merge which are similar, and the merged submission should be in the span of the two original submissions.”

2018.08: first merge announcement

2018.08.04: HILA5 and Round2 merge to form Round5.

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- Decryption failures are much more likely than claimed.
- For many earlier lattice systems, presumably also for Round5: can break system using a small number of decryption failures.
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Round5 response: "proposed fix"; "looking at the security proof adjustments"; "actual Round5 proposal to NIST is still months away."

National Academy of Sciences report

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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."