Migrating to the McEliece cryptosystem

Daniel J. Bernstein

Goal: Long-term security

Want to ensure that application data is solidly protected for the foreseeable future.

Goal: Long-term security

Want to ensure that application data is solidly protected for the foreseeable future.

Typical application today is not achieving this:

- Application relies on ECC (ECDH) for public-key encryption.
- Attackers today are recording the application's ECC-encrypted data.
- Attackers will use future quantum computers to break the encryption.

Goal: Long-term security

Want to ensure that application data is solidly protected for the foreseeable future.

Typical application today is not achieving this:

- Application relies on ECC (ECDH) for public-key encryption.
- Attackers today are recording the application's ECC-encrypted data.
- Attackers will use future quantum computers to break the encryption.

Typical response: Upgrade to post-quantum encryption. **But is the new system secure?**

Example of a failure: SIKE

2011: SIKE is published, says it is better than previous isogeny-based cryptosystems.

2017: SIKE is submitted to NIST competition.

2019: Google and Cloudflare upgrade many users' HTTPS connections to use SIKE.

Example of a failure: SIKE

2011: SIKE is published, says it is better than previous isogeny-based cryptosystems.

2017: SIKE is submitted to NIST competition.

2019: Google and Cloudflare upgrade many users’ HTTPS connections to use SIKE.

2022: NIST selects SIKE as just one of four candidates for further consideration.
“SIKE remains an attractive candidate for standardization because of its small key and ciphertext sizes.”

Example of a failure: SIKE

2011: SIKE is published, says it is better than previous isogeny-based cryptosystems.

2017: SIKE is submitted to NIST competition.

2019: Google and Cloudflare upgrade many users' HTTPS connections to use SIKE.

2022: NIST selects SIKE as just one of four candidates for further consideration.
"SIKE remains an attractive candidate for standardization because of its small key and ciphertext sizes."

2022: Attacks are published that break SIKE.

Options for SIKE upgrades

	short-term security	long-term security
Goal	yes	yes
Pre-upgrade: ECC	yes	no

Options for SIKE upgrades

	short-term security	long-term security
Goal	yes	yes
Pre-upgrade: ECC	yes	no
Option 1: SIKE	no	no

Option 1: Encrypt with SIKE
and *remove* previous ECC encryption.

Options for SIKE upgrades

	short-term security	long-term security
Goal	yes	yes
Pre-upgrade: ECC	yes	no
Option 1: SIKE	no	no
Option 2: ECC+SIKE	yes	no

Option 1: Encrypt with SIKE
and *remove* previous ECC encryption.

Option 2, what Google and Cloudflare did:
Encrypt with ECC *and* encrypt with SIKE.
“Double encryption”; “hybrid encryption”.

Many more failures

Out of 69 submissions in 2017
to the NIST competition from 260 people,
28% are now known to be breakable:

CFPKM	Compact LWE	DME	Edon-K
Giophantus	Guess Again	HK17	LUOV-7
MQDSS	pqsigRM	qTESLA-s	RaCoSS
Rainbow-1	RankSign	Round2	RVB
SIKE	SRTPI	WalnutDSA	

Many more failures

Out of 69 submissions in 2017
to the NIST competition from 260 people,
28% are now known to be breakable:

CFPKM	Compact LWE	DME	Edon-K
Giophantus	Guess Again	HK17	LUOV-7
MQDSS	pqsigRM	qTESLA-s	RaCoSS
Rainbow-1	RankSign	Round2	RVB
SIKE	SRTPI	WalnutDSA	

Attack algorithms have improved against
almost all of the remaining submissions.

Example of the dangers

FrodoKEM says it is the most conservative lattice-based system: an “instantiation and implementation” of 2010 Lindner–Peikert.

2010 Lindner–Peikert proposed dimension **256** to “**currently** offer security levels at least matching those of AES-128” (emphasis added).

Example of the dangers

FrodoKEM says it is the most conservative lattice-based system: an “instantiation and implementation” of 2010 Lindner–Peikert.

2010 Lindner–Peikert proposed dimension **256** to “**currently** offer security levels at least matching those of AES-128” (emphasis added).

Many newer advances in attacks have been published. 2010 Lindner–Peikert proposal has *much* lower security level than AES-128.

Example of the dangers

FrodoKEM says it is the most conservative lattice-based system: an “instantiation and implementation” of 2010 Lindner–Peikert.

2010 Lindner–Peikert proposed dimension **256** to “**currently** offer security levels at least matching those of AES-128” (emphasis added).

Many newer advances in attacks have been published. 2010 Lindner–Peikert proposal has *much* lower security level than AES-128.

FrodoKEM claims dimension **640** matches AES-128 with a “comfortable security margin”.

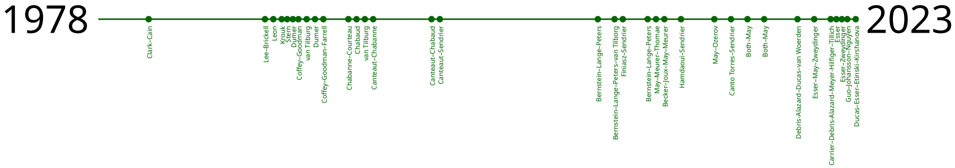
McEliece's cryptosystem is different

(Robert J. McEliece, 1942–2019)

The McEliece cryptosystem
was published in 1978 and has
a remarkably stable security level
despite many papers trying to break it.

Stability metric #1: asymptotics

$$\lim_{K\to\infty} \frac{\log_2 \text{AttackCost}_{\text{year}}(K)}{\log_2 \text{AttackCost}_{2023}(K)}$$

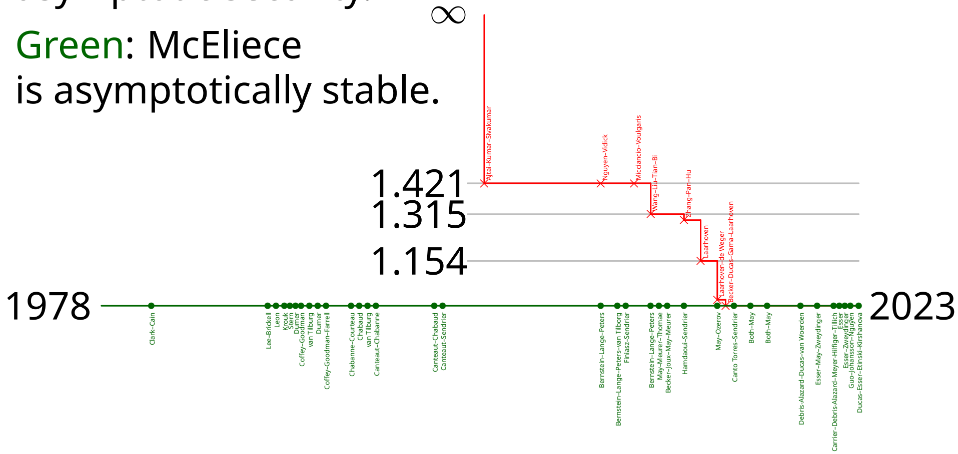


Stability metric #1: asymptotics

$$\lim_{K\to\infty} \frac{\log_2 \mathrm{AttackCost}_{\mathrm{year}}(K)}{\log_2 \mathrm{AttackCost}_{2023}(K)}$$

Red: Lattices keep losing asymptotic security.

Green: McEliece is asymptotically stable.



Stability metric #2: challenges

Important McEliece parameter: “length”.

There are scaled-down challenges to see what lengths academics can break.

The two most recent records:

- Length-1284 challenge broken as title of a Eurocrypt 2022 paper.

Stability metric #2: challenges

Important McEliece parameter: “length”.

There are scaled-down challenges to see what lengths academics can break.

The two most recent records:

- Length-1284 challenge broken as title of a Eurocrypt 2022 paper.
- Length-1347 challenge broken using the 2008 Bernstein–Lange–Peters software.

Stability metric #2: challenges

Important McEliece parameter: “length”.

There are scaled-down challenges to see what lengths academics can break.

The two most recent records:

- Length-1284 challenge broken as title of a Eurocrypt 2022 paper.
- Length-1347 challenge broken using the 2008 Bernstein–Lange–Peters software.

The 2008 software is as fast as the 2022 software. The records come from running attacks on larger computer clusters.

Stability metric #3: bit operations

2023 Bernstein–Chou "CryptAttackTester: high-assurance attack analysis": software to

- build complete attack circuits,
- predict circuit cost and probability,
- run small attacks to check accuracy.

Bit operations predicted by CryptAttackTester to attack `mceliece348864` (length 3488):

- $2^{156.96}$: `isd1`, attack ideas from the 1980s.
- $2^{150.59}$: `isd2`, latest attacks.

What about quantum computers?

McEliece attacks, like AES attacks,
are bottlenecked by big searches.

Replacing searches with quantum searches
(and “random walks” with “quantum walks”)
at worst chops exponents in half.
Probably actual impact is much smaller.

Classic McEliece parameter selections
use lengths 3488, 4608, 6688, 6960, 8192.
6688, 6960 are recommended for long-term
“will never have to change this” security.

Another security metric: tightness

1978 McEliece system was designed to be one-way. This is the natural mathematical concept of security for public-key encryption, but does not stop chosen-ciphertext attacks.

Another security metric: tightness

1978 McEliece system was designed to be one-way. This is the natural mathematical concept of security for public-key encryption, but does not stop chosen-ciphertext attacks.

2017 "Classic McEliece" has CCA protection. QROMCCASecLevel(Classic McEliece) $\geq$ OneWaySecLevel(1978 McEliece) $-$ **5**.

Another security metric: tightness

1978 McEliece system was designed to be one-way. This is the natural mathematical concept of security for public-key encryption, but does not stop chosen-ciphertext attacks.

2017 “Classic McEliece” has CCA protection. QROMCCASecLevel(Classic McEliece) $\geq$ OneWaySecLevel(1978 McEliece) $-$ **5**.

For comparison, typical lattice proof says: QROMCCASecLevel(lattice-based system) $\geq$ OneWaySecLevel(new lattice problem) $-$ **100**. Actually, most proofs are worse than this.

Lattices strike back

Lattices strike back

"The `mceliece6960119` public key is 1MB. That's unusable."

OK, let's talk about performance

1MB is very fast on a modern network.
Are Netflix and YouTube unusable?

OK, let's talk about performance

1MB is very fast on a modern network.
Are Netflix and YouTube unusable?

Quantify the costs in context.
See if they're affordable. Skip the hype.
(Should decisions be based on hype wars?)

OK, let’s talk about performance

1MB is very fast on a modern network.
Are Netflix and YouTube unusable?

Quantify the costs in context.
See if they’re affordable. Skip the hype.
(Should decisions be based on hype wars?)

McEliece is already used in some end-to-end secure-messaging systems and the Mullvad and Rosenpass VPNs. Recommended by BSI (Germany) and NCSC (Netherlands). Under consideration by NIST and by ISO.

Revenge of the lattices

Revenge of the lattices

"Even if McEliece is usable,
it's much bigger than lattices.
Sending extra network traffic
damages the environment."

Want to minimize cost? Reuse keys!

Google's public key can be used to protect **any number of ciphertexts** to/from Google.

Ciphertexts have to be sent end-to-end, and usually have to be sent immediately, even if you're on an expensive network.

Public keys can be **shared locally** through existing caching mechanisms (e.g., DNS), and can be distributed in advance.

Want to minimize cost? Reuse keys!

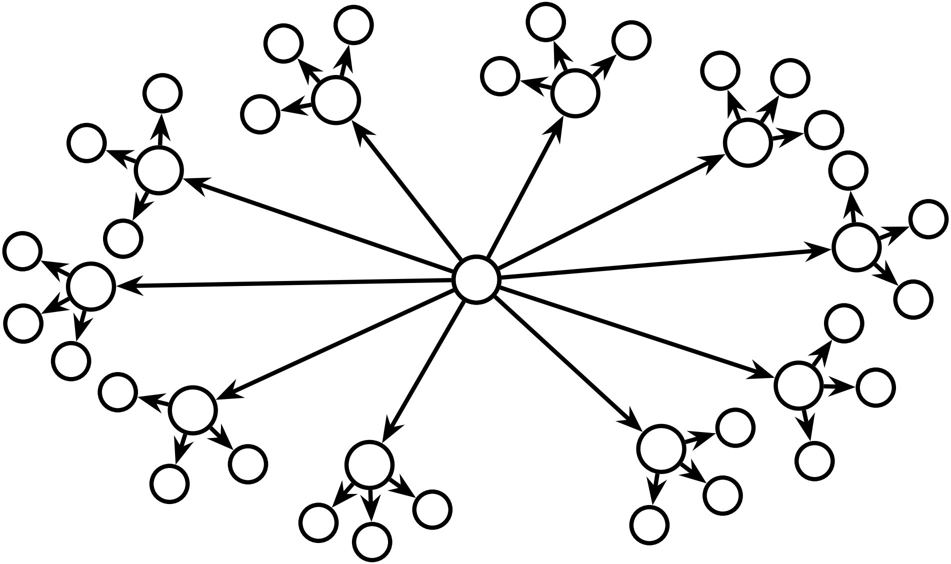
Google's public key can be used to protect **any number of ciphertexts** to/from Google.

Ciphertexts have to be sent end-to-end, and usually have to be sent immediately, even if you're on an expensive network.

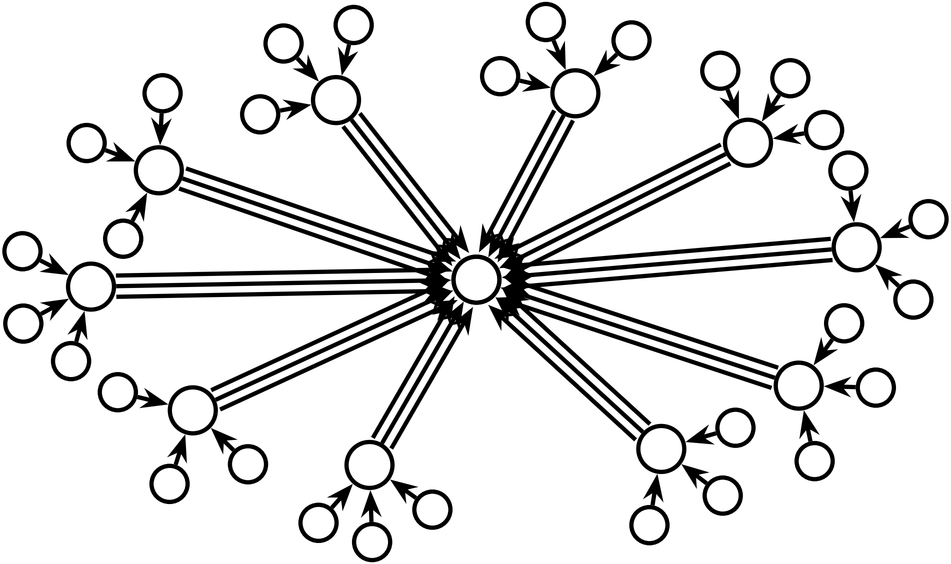
Public keys can be **shared locally** through existing caching mechanisms (e.g., DNS), and can be distributed in advance.

Next slide: 1 site; 10 ISPs; 3 users per ISP.
Real world: can easily be 20000 users per ISP.

Public keys out, ciphertexts in



Public keys out, ciphertexts in



The McEliece size advantage

The site's public key, M	1047319 bytes
The site's public key, K	800 bytes
Each user's ciphertext, K	768 bytes
Each user's ciphertext, M	194 bytes
20000 ct + 20000 pk copies, M	20950260000 bytes
20000 ct + 20000 pk copies, K	31360000 bytes
20000 ct + 1 pk copy, K	15360800 bytes
20000 ct + 1 pk copy, M	4927319 bytes

If we're trying to minimize environmental impact, we should aim for the last line.

The McEliece size advantage

The site's public key, M	1047319 bytes
The site's public key, K	800 bytes
Each user's ciphertext, K	768 bytes
Each user's ciphertext, M	194 bytes
20000 ct + 20000 pk copies, M	20950260000 bytes
20000 ct + 20000 pk copies, K	31360000 bytes
20000 ct + 1 pk copy, K	15360800 bytes
20000 ct + 1 pk copy, M	4927319 bytes

If we're trying to minimize environmental impact, we should aim for the last line.

K: `kyber512`.
M: `mceliece6960119`, much higher security.

Classic McEliece implementations

Official software for Classic McEliece is distributed via SUPERCOP benchmarking framework. Four implementations for each parameter set, all passing TIMECOP:

- `ref`: portable, prioritizing simplicity.
- `vec`: portable, 64-bit vectorization.
- `sse`: Intel/AMD, 128-bit vectorization.
- `avx`: Intel/AMD, 256-bit vectorization.

Unofficial: Bouncy Castle (Java and C#), Rust, M4, FPGAs, McTiny, McOutsourcing.
Integrations: PQClean, liboqs, Node.js.
New: Easy-to-use libmceliece.

PROTECT THE USERS

MCELIECE

SAVE THE ENVIRONMENT