MAX PLANCK INSTITUTE
FOR SECURITY AND PRIVACY

6 years of NIST PQC – looking back and ahead

Peter Schwabe

September 29, 2022

Part I – looking back

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- Cryptographic engineering point of view

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- Cryptographic engineering point of view
- Looking back at 6 years of NIST PQC:
  - What went well
  - What went not so well

Part I – looking back

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- Cryptographic engineering point of view
- Looking back at 6 years of NIST PQC:
  - What went well (in work by other people)
  - What went not so well (in “our submissions”)

Our submissions

CRYSTALS-Kyber

Roberto Avanzi
Joppe Bos
Jintai Ding
Léo Ducas
Eike Kiltz
Tancrède Lepoint
Vadim Lyubashevsky
John M. Schanck
Peter Schwabe
Gregor Seiler
Damien Stehle

CRYSTALS-Dilithium

Léo Ducas
Eike Kiltz
Tancrède Lepoint
Vadim Lyubashevsky
Peter Schwabe
Gregor Seiler
Damien Stehlé
Shi Bai

SPHINCS$^+$

Jean-Philippe Aumasson
Daniel J. Bernstein
Ward Beullens
Christoph Dobraunig
Maria Eichlseder
Scott Fluhrer
Stefan-Lukas Gazdag
Andreas Hülsing
Panos Kampanakis
Stefan Kölbl
Tanja Lange
Martin M. Lauridsen
Florian Mendel
Ruben Niederhagen
Christian Rechberger
Joost Rijneveld
Peter Schwabe
Bas Westerbaan

1. Designing

"A complete written specification of the algorithms shall be included, consisting of all necessary mathematical operations, equations, tables, diagrams, and parameters that are needed to implement the algorithms. The document shall include design rationale and an explanation for all the important design decisions that are made"

—Dustin Moody, February 24, 2016 (PQCRYPTO 2016)

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- Choose concrete parameters for different security levels
- All randomness from `randombytes` or just a seed?
- Fix sampling algorithms (e.g., constant-time sorting)
- Select symmetric primitives
- Concretize domain separation

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- Choose concrete parameters for different security levels
- All randomness from `randombytes` or just a seed?
- Fix sampling algorithms (e.g., constant-time sorting)
- Select symmetric primitives
- Concretize domain separation
- **Tradeoffs, tradeoffs, tradeoffs**. . .

1. Designing – Exhibit A

Dilithium – v3.0 vs. v3.1

$\underline{\mathsf{Sign}(sk, M)}$
09 $\mathbf{A} \in R_q^{k \times \ell} := \mathsf{ExpandA}(\rho)$
10 $\mu \in \{0,1\}^{384} := \mathsf{CRH}(tr \parallel M)$
11 $\kappa := 0,\ (\mathbf{z}, \mathbf{h}) := \perp$

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09 $\mathbf{A} \in R_q^{k \times \ell} := \mathsf{ExpandA}(\rho)$
10 $\mu \in \{0,1\}^{512} := \mathrm{H}(tr \parallel M)$
11 $\kappa := 0,\ (\mathbf{z}, \mathbf{h}) := \perp$

- Message hash only 384 bits
- 192 bits of sec. against collisions
- Not sufficient for NIST level 5

1. Designing – Exhibit B

SPHINCS$^+$, round 3

- Security relies on DM — SPR (Distinct-function multi-target second preimage resistance) of underlying hash function
- Three different choices of hash function: SHA-256, SHAKE-256, Haraka

1. Designing – Exhibit B

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"This is an interesting attack that does demonstrate that our real hash functions do not perfectly behave like random oracles"

—Andreas Hülsing, April 21, 2022

1. Designing – Two questions

1. Will the schemes selected now be widely used?

2. Will those schemes survive in the long run?

2. Proving

"Submitters are not required to provide a proof of security, although such proofs will be considered if they are available."

—NIST PQC, Call for Proposals

2. Proving – Exhibit A

Kyber round 1

- LPR scheme's public key is $\mathbf{t} = \mathbf{As} + \mathbf{e}$
- This is an (R/M)LWE sample and assumed to be uniform in the proof

2. Proving – Exhibit A

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- This is an (R/M)LWE sample and assumed to be uniform in the proof
- Kyber in round 1 compressed this (round off low bits)
- $\mathbf{t}' = \text{Decompress}(\text{Compress}(\mathbf{t}))$ is **not** uniform

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- This is an (R/M)LWE sample and assumed to be uniform in the proof
- Kyber in round 1 compressed this (round off low bits)
- $\mathbf{t}' = \text{Decompress}(\text{Compress}(\mathbf{t}))$ is **not** uniform
- Reduction from MLWE in round-1 Kyber was invalid:

"We note that a potential issue is that the security proof does not directly apply to Kyber itself, but rather to a modified version of the scheme which does not compress the public key."

—NIST IR 8240

2. Proving – Exhibit B

SPHINCS$^+$ – original proof

- Reduce from second-preimage resistance
- Place challenge $x = H(y)$ inside hash chains
- Forgery produces preimage of x with certain prob.
- Reduction hopes to obtain second preimage $y' \neq y$ with $x = H(y')$

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- Problem: $\text{len}(x) = \text{len}(y)$
- Second preimage does not exist with high probablity
- Forger **can refuse to forge if there is a second preimage**

2. Proving – so many failure modes

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- Proof correct, but theorem "insufficient"
  - Example: attack hides in non-tightness
- Proof (and possibly theorem) too vague
- Theorem and proof correct, but not very useful

  "A is secure if A is secure"

3. Implementing

"NISTPQC, despite being an important and timely project, has produced the largest regression ***ever*** *in the quality of cryptographic software. This will not be easy to fix."*

—Daniel J. Bernstein, October 5, 2018

3. Implementing – Exhibit A

Dilithium commit on Dec. 28, 2017

```
212         -     t  = buf[pos];
213         -     t |= (uint32_t)buf[pos + 1] << 8;
214         -     t |= (uint32_t)buf[pos + 2] << 16;
215         -     t &= 0xFFFFF;
        337 +     t0  = buf[pos];
        338 +     t0 |= (uint32_t)buf[pos + 1] << 8;
        339 +     t0 |= (uint32_t)buf[pos + 2] << 16;
        340 +     t0 &= 0xFFFFF;
216     341
217         -     t  = buf[pos + 2] >> 4;
218         -     t |= (uint32_t)buf[pos + 3] << 4;
219         -     t |= (uint32_t)buf[pos + 4] << 12;
        342 +     t1  = buf[pos + 2] >> 4;
        343 +     t1 |= (uint32_t)buf[pos + 3] << 4;
        344 +     t1 |= (uint32_t)buf[pos + 4] << 12;
```

- Bug in Dilithium sampler
- Two consecutive coefficients are equal
- Allows key recovery
- Reported by Peter Pessl on Dec. 27, 2017

3. Implementing – Exhibit B

PQClean

- Joint work with Matthias Kannwischer, Joost Rijneveld, John Schanck, Douglas Stebila, Goutam Tamvada, Thom Wiggers
- Test harness for PQC implementations
- Integrate reference implementations
  - Run through test harness
  - “clean up”

3. Implementing – Exhibit B

Flaw	KEMs	Sigs	Flaw	KEMs	Sigs
Memory safety	3	4	Endianness assumptions	7	2
Signed integer overflow	3	1	Platform-specific behavior	4	0
Alignment assumptions	4	4	Variable-Length Arrays	4	1
Other Undefined Behavior	1	1	Compiler extensions	5	2
Dead code	3	4	Integer sizes	6	3
Global state	2	1	Non-constant time	4	0
Licensing unclear	3	1			

3. Implementing – Exhibit B

"In almost every scheme we identified "unclean" code, ranging from missing casts to memory safety problems and other forms of undefined behavior."

—https://eprint.iacr.org/2022/337

3. Implementing – Exhibit C

Questions about the range analysis of iNTT for "Faster Kyber and Dilithium on the Cortex-M4" #226

Closed **JunhaoHuang** opened this issue on Mar 3 · 4 comments

JunhaoHuang commented on Mar 3 • edited

Hi team, I am reading the Kyber code regarding the recent paper "Faster Kyber and Dilithium on the Cortex-M4", and I have a question about the matrix-vector product and Better Accumulation part regarding the *f_stack* version code.

I see that using the better accumulation technique in the f_speed version code, we can reduce each element of the output vector of matrix-vector product down to (-q,q). Since poly_invntt is normally used after the matrix-vector product, the range of the input vector of **poly_invntt** lies in (-q,q) in the *f_speed* version code. The **invntt** function works in this situation.

What I wonder is that in the *f_stack* version code, the **matacc** function actually uses the previous double basemul accumulation function, and it should produce the result vector with element in (-kq, kq), k is the security parameter of Kyber. For Kyber1024, the range of each polynomial element that **invntt** takes should be (-4q,4q). However, the **invntt** function is the same as the f_speed version code. The first four layers of the light butterflies in **invntt** involve some additions and subtractions without multiplication. Therefore, For Kyber1024 in the *f_stack* version code, two layers of addition/subtraction might overflow the int16_t. I wonder how you deal with this problem in the *f_stack* code and why does it still work?

Assignees
No one assigned

Labels
None yet

Projects
None yet

Milestone
No milestone

Development
No branches or pull requests

3. Implementing – Exhibit C

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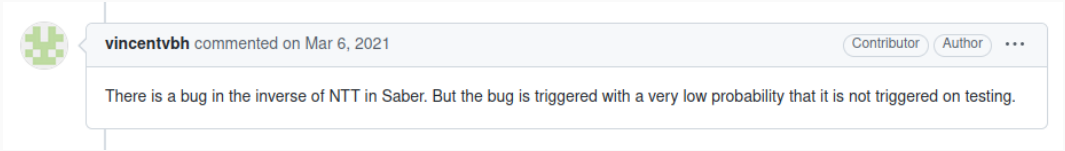
"... two layers of addition/subtraction might overflow the int16_t. I wonder how you deal with this problem in the f_stack code and why does it still work?"

"... On your question on why it still works, I believe that this is an edge case that does not get triggered by the testing scripts."

3. Implementing – Exhibit C



vincentvbh commented on Mar 6, 2021 Contributor Author •••

There is a bug in the inverse of NTT in Saber. But the bug is triggered with a very low probability that it is not triggered on testing.

4. Attacking

"The idea is that participants put their algorithms into the ring, and then we all spend a few years beating on each other's submissions."

—Bruce Schneier, August 8, 2022

4. Attacking – Guessed Once

```
def recover_bit(ct, bit):
    assert bit < len(ct) // 4000
    ts = [struct.unpack('BB', ct[i:i+2]) for i in range(4000*bit, 4000*(bit+1), 2)]
    xs, ys = [a for a, b in ts if b == 1], [a for a, b in ts if b == 2]
    return sum(xs) / len(xs) >= sum(ys) / len(ys)

def decrypt(ct):
    res = sum(recover_bit(ct, b) << b for b in range(len(ct) // 4000))
    return int.to_bytes(res, len(ct) // 4000 // 8, 'little')
```

—Lorenz Panny, December 21, 2017

4. Attacking in 2022

ia.cr/2022/975

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Castryck, Decru: *An efficient key recovery attack on SIDH*

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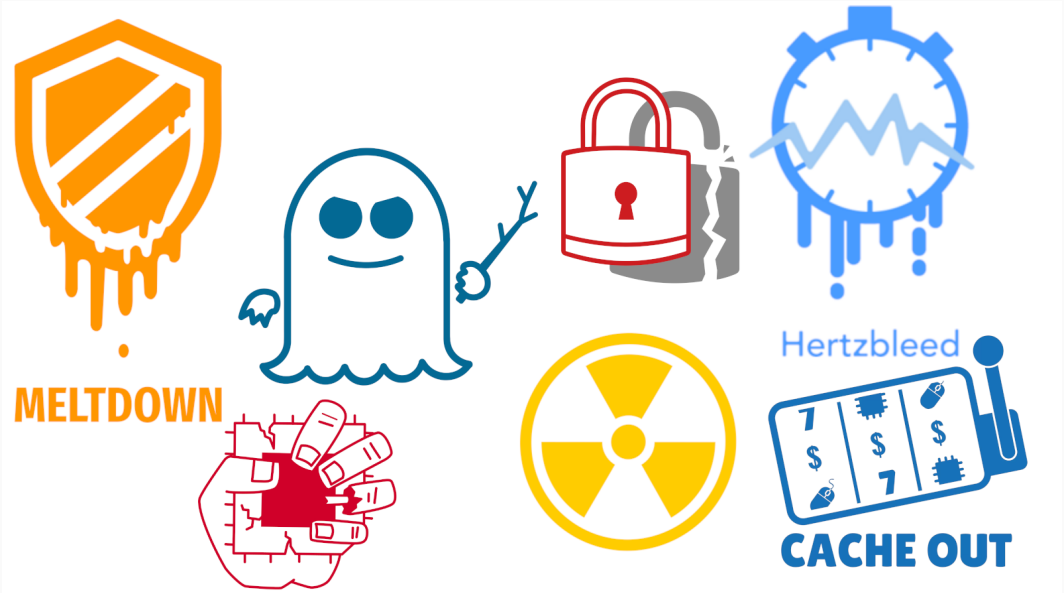
Yet, **full break without any “warning”**

4. Attacking – even more attacks!



5. Communicating

"I don't know if you're familiar with this website, twitter.com? If you like crypto drama, this is where you go. Except if you go to the pqc-forum, which is also... generally... it's even better".

—Bor de Kock, August 17, 2022

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`https://www.youtube.com/watch?v=kXcYy8LOI9s`, starting at 20:22.

5. Communicating – pqc-forum

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*"**Follow the "Rule of 1" and the "Rule of n":** When you speak, make 1 point and then let others speak, and when in a group of "n" people, speak "1/nth" of the time."*

—Aspiration Participants:Guidelines

`https://facilitation.aspirationtech.org/index.php?title=Participants:Guidelines`

5. Communicating – pqc-forum

Download all mails, run statistics

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Download almost all mails, run statistics

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- pqc-forum had 666 threads (“conversations”) on Sep. 14, 2022
- First mail by Dustin Moody from Aug. 1, 2016
- I have 2805 mails (first one from Nov. 2, 2016)

5. Communicating – pqc-forum

```
for i in mails/*;do
  FROM=$(grep ^From: $i | head -n 1 | sed "s/From:\ //" | sed "s/.*<\([^>]*\)>/\1/")
  if [ "$FROM" = "pqc-forum@list.nist.gov" ]; then
    FROM=$(grep ^X-Original-From: $i | head -n 1 | \
      sed "s/X-Original-From:\ //" | sed "s/.*<\([^>]*\)>/\1/")
  fi
  echo $FROM
done | sort | uniq -c | sort -n
```

- 369 sender addresses
- Sometimes multiple addresses for one person
- 131 addresses sent just one mail
- 275 addresses sent at most 5 mails

5. Communicating – pqc-forum

The “Top 10”

1.	`address1`	407
2.	`address2`	146
3.	`address3`	113
4.	`address4`	106
5.	`address5`	100
6.	`address6`	81
7.	`address7`	69
8.	`address8`	68
9.	`address9`	50
10.	`address10`	47
10.	`address11`	47

5. Communicating – pqc-forum

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>50% of mails sent by only 15 people.

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>50% of mails sent by only 15 people.

>30% of all words by *non-NIST* authors are from one address.

Part II – looking ahead

- More designing, proving, implementing, attacking, communicating in rounds 4, 5, 6,. . .
- Additional scrutiny of selected algorithms
- Standardization and deployment of selected algorithms

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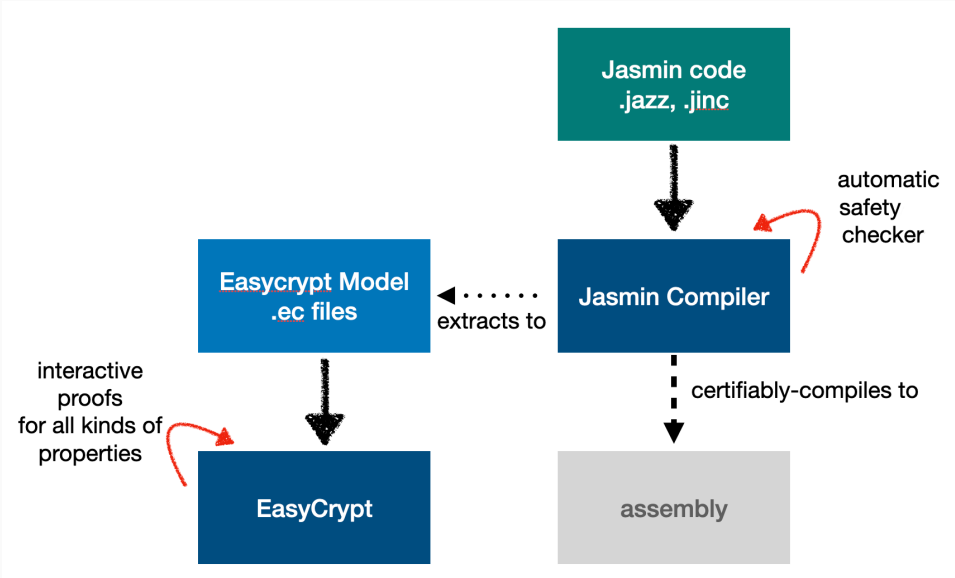
Formosa Crypto

- Effort to formally verify crypto
- Currently three main projects:
  - EasyCrypt proof assistant
  - jasmin programming language
  - libjade (PQ-)crpyto library
- Core community of $\approx$ 30–40 people
- Discussion forum with $>$100 people

The toolchain and workflow



Programming in jasmin – “assembly in the head”

- Syntax is very C like
- Compilation is much more predictable:
  - Generally: 1 line in jasmin $\rightarrow$ 1 line in asm
  - A few exceptions, but highly predictable
  - Compiler does not schedule code
  - Compiler does not spill registers, syntactically correct code may fail to compile!

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  - Compiler does not schedule code
  - Compiler does not spill registers, syntactically correct code may fail to compile!
- Compiler is formally proven to preserve semantics
- Compiler is formally proven to preserve constant-time property
- Separate compiler run to ensure memory safety (statically!)

(Speculative) constant-time

Guaranteed constant-time code

- Information-flow type system, distinguish high (secret) and low (public) data
- Prevent branching and memory indexing on secret data
- Compilation is proven to preserve this property!

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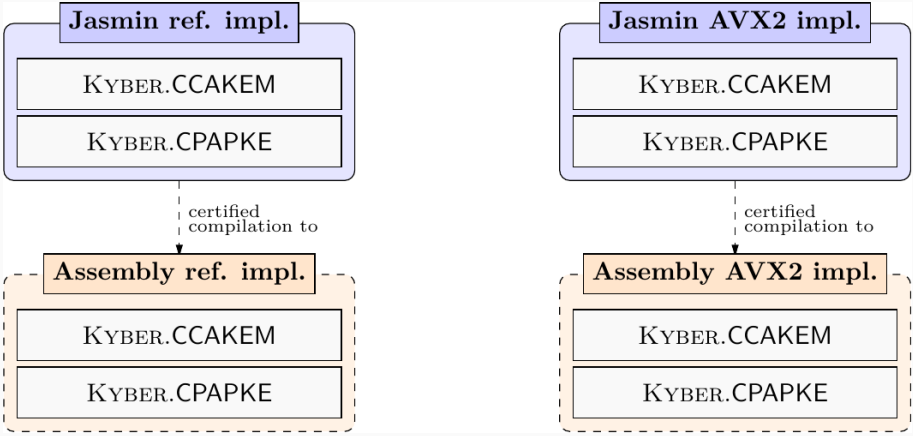
Guaranteed Spectre v1 protection

- Extend type system: “transient” (public, but may be secret during misspeculation)
- Keep predicate to track misspeculation
- Mask transient data with predicate
- Approach is **Selective Speculative Load Hardening (selSLH)**
- Performance overhead for crypto: $<1\%$

Basavesh Ammanaghatta Shivakumar, Gilles Barthe, Benjamin Grégoire, Vincent Laporte, Tiago Oliveira, Swarn Priya, Peter Schwabe, Lucas Tabary-Maujean: *Typing High-Speed Cryptography against Spectre v1.* `https://eprint.iacr.org/2022/1270`

Formally verified Kyber (WIP)



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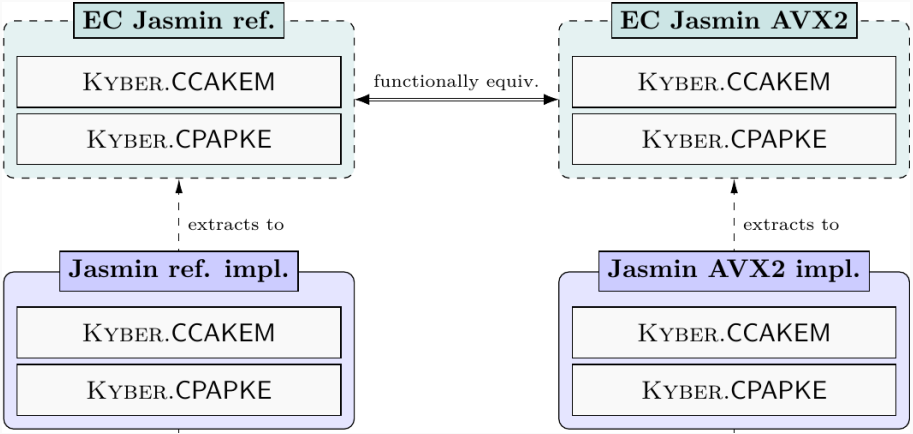

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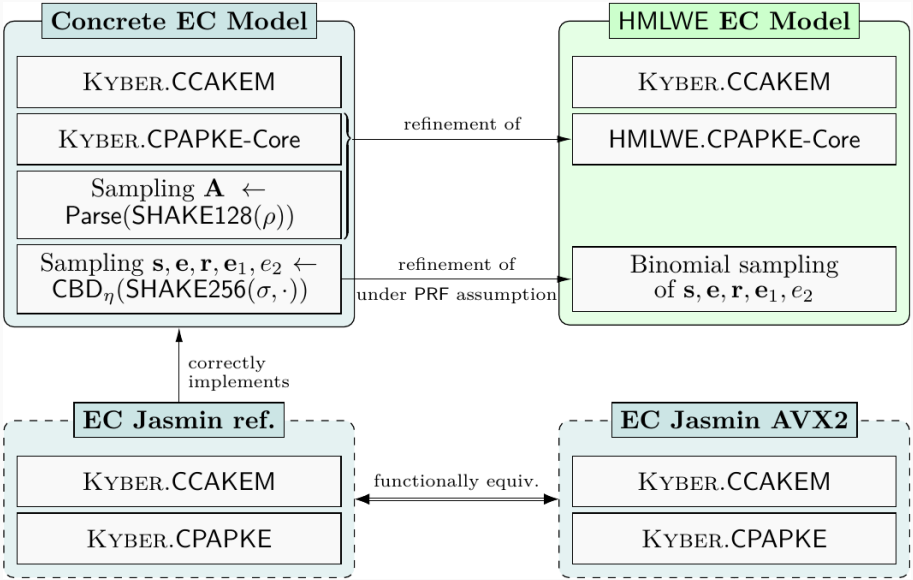

Formally verified Kyber (WIP)

- Connect to EasyCrypt IND-CPA proof of HMLWE.CPAPKE-Core EC model
- Connect to EasyCrypt IND-CCA proof of HMLWE.CCAKEM EC model

Joint work with José Bacelar Almeida, Manuel Barbosa, Gilles Barthe, Benjamin Grégoire, Andreas Hülsing, Vincent Laporte, Jean-Christophe Léchenet, Tiago Oliveira, Hugo Pacheco, Miguel Quaresma, Antoine Séré, and Pierre-Yves Strub

What if. . . ?

Had NIST required computer-verified software and proofs,

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- we would have had way fewer bugs in PQC software;
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- we would have had way fewer bugs in PQC software;
- we would have much higher confidence in all proofs;
- attacks could be much more focused;
- we could heavily reduce “noise” in discussions;

What if. . . ?

Had NIST required computer-verified software and proofs,

- we would have had way fewer bugs in PQC software;
- we would have much higher confidence in all proofs;
- attacks could be much more focused;
- we could heavily reduce “noise” in discussions;

. . . and we would probably not have had a single submission.

Interested? Get involved!

https://formosa-crypto.org

https://formosa-crypto.zulipchat.com/