My personal experience with the NIST PQC "competition"

MAX PLANCK INSTITUTE
FOR SECURITY AND PRIVACY

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- I'll try to avoid finger-pointing

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- All 7 advanced to round 2
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- ERC StG project “EPOQUE – Engineering post-quantum cryptography”
    - Efficient and secure implementation of PQC
    - Design of post-quantum protocols

7 submissions

KEMs

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- Albrecht, Bernstein, Chou, Cid, Gilcher, Lange, Maram, von Maurich, Misoczki, Niederhagen, Paterson, Persichetti, Peters, Schwabe, Sendrier, Szefer, Tjhai, Tomlinson, and Wang: **Classic McEliece**

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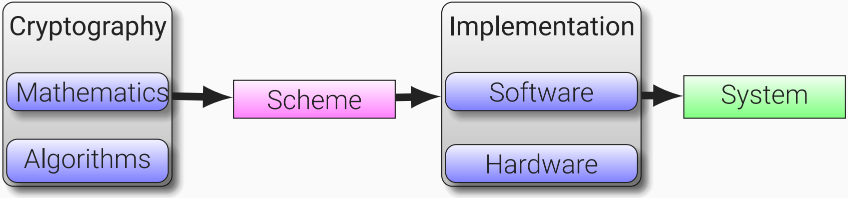
- Hülsing, Aumasson, Bernstein, Beullens, Dobraunig, Eichlseder, Fluhrer, Gazdag, Kampanakis, Kölbl, Lange, Lauridsen, Mendel, Niederhagen, Rechberger, Rijneveld, Schwabe, and Westerbaan: SPHINCS$^+$

Cryptographic Engineering

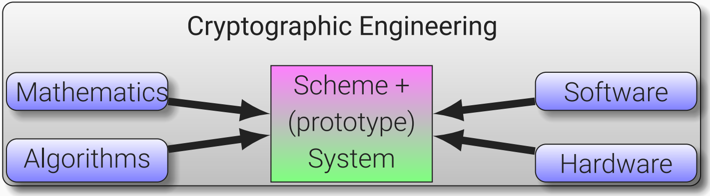
Designing and building cryptographic systems

The traditional approach



Designing and building cryptographic systems

A holistic approach



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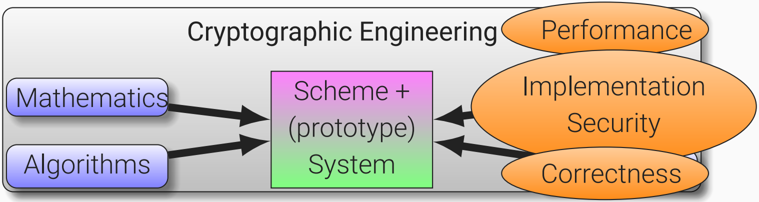

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Parallel SHAKE in Kyber

- Kyber-768 needs to sample 9 polynomials uniformly mod q
- Use rejection sampling on SHAKE output
- 9 independent invocations of SHAKE (more output required!)
- Can vectorize SHAKE: much faster
- Easy to implement with low memory footprint on μc

Examples, part II

Avoid fixed-weight sampling

- Fixed-weight sampling lowers failure prob. for lattice-based KEMs
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Tweakable hash functions

- Software of SPHINCS$^+$ modularized
- Abstraction layer: “tweakable hash functions”
- Idea: Use also to modularize the proof

Part I

Software implementations

NIST PQC software requirements

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- Some permitted external dependencies: NTL, GMP, OpenSSL, XKCP
- API following SUPERCOP API:
    - signing produces **signed message** instead of signature
    - randomness sampled internally
    - no batching of crypto operations

“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, Oct. 2018

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- Out-of-bound reads, need zeroes in memory
- Out-of-bound writes, hope for the best

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- Decaps returning -1 on failure in Kyber
- Timing leaks in many implementations
  - Often timing-attack resistance not claimed
  - Sometimes violating constant-time claims

Underlying reasons (?)

- Different understanding of “cryptographic software”
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- ANSI C (i.e., without intrinsics) not useful to illustrate performance
- Multiple teams without an “implementor”
- New schemes: no existing test vectors, yet
- Unnecessarily hard to get it right

Some ideas how to do better

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- Provide access to benchmarking platforms (for optimized code)

PQClean

- Joint work with
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- Longer-term, if there is interest:
  - implementations with architecture-specific optimizations (WIP)
  - implementations in other languages?

The definition of “clean”

- Code is valid C99
- Passes functional tests
- API functions do not write outside provided buffers
- API functions do not need pointers to be aligned
- Compiles with -Wall -Wextra -Wpedantic -Werror with gcc and clang
- Compiles with `/W4 /WX` with MS compiler
- Consistent test vectors across runs
- Consistent test vectors on big-endian and little-endian machines
- Consistent test vectors on 32-bit and 64-bit machines

The definition of "clean"

- No errors/warnings reported by valgrind
- No errors/warnings reported by address sanitizer
- No errors/warnings reported by undefined-behavior sanitizer
- Only dependencies:
    - `fips202.c`
    - `sha2.c`
    - `aes.c`
    - `randombytes.c`

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- Builds under Linux, MacOS, and Windows without warnings
- All exported symbols are namespaced with `PQCLEAN_SCHEMENAME_`
- Each implementation comes with license and meta information in `META.yml`

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- Argument names consistent between `.h` and `.c` files

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- Valgrind does not work with environments running on qemu

Benchmarking software in NISTPQC

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Benchmarking software in NISTPQC

Problem with this approach

- Benchmarks **are not independent**
- Massive overlap between sets of submitters and “benchmarkers”
- Unfair advantage for those submitters?
- Possibly more fair approach:
    - Fix a few target **micro**architectures
    - Publish benchmarking software long ahead of time
    - If needed, give submitters access to platforms for optimizations

Beyond C

- How about Sage/Python for reference implementation?
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- How about using hacspec?
  - Subset of Rust; see `https://hacspec.github.io/`
  - "A specification language for crypto primitives and more"
  - Interfaces to verification frameworks
  - Work towards goal of **high-assurance crypto**

Part II

Random thoughts

The pqc-forum mailing list

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- Essentially all comments are subjective/biased:
  - Submitters have something to gain/lose
  - Companies have started implementing/investing
  - Selection bias (optimize own scheme, attack low-hanging fruits)
  - Very incomplete picture (e.g., for SCA)

Security levels and metric

NIST approach: relate to AES/SHA2/SHA3 security

"computational resources may be measured using a variety of different metrics (e.g., number of classical elementary operations, quantum circuit size, etc.). In order for a cryptosystem to satisfy one of the above security requirements, any attack must require computational resources comparable to or greater than the stated threshold, with respect to all metrics that NIST deems to be potentially relevant to practical security.

NIST intends to consider a variety of possible metrics, reflecting different predictions about the future development of quantum and classical computing technology. NIST will also consider input from the cryptographic community regarding this question."

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Ignore classical attacks

- Concrete security of PQ schemes still not as stable as ECC
- Near-future deployment: use hybrid
- Long term: classical security won’t matter

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- Curious to see more elaborate throughput-optimized signatures

NIKEs

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- Some work towards lattice-based NIKE; see
  - "Folklore" (Lyubashevsky): `https://tinyurl.com/r5eb8su8`
  - de Kock (Master's thesis, TU/e, 2018): *"A non-interactive key exchange based on ring-learning with errors"*
  - Guo, Kamath, Rosen, Sotiraki (PKC 2020): *"Limits on the Efficiency of (Ring) LWE Based Non-interactive Key Exchange"*

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How confident can we be in proofs when schemes are standardized?

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Computer-verified proofs

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- of implementation correctness
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Work in progress

- High-speed implementation of Kyber in jasmin (`https://github.com/jasmin-lang/jasmin`)
- Proof that implementation matches spec in EasyCrypt (`https://github.com/EasyCrypt/easycrypt`)
- Proof that spec achieves CCA security in EasyCrypt
- See talk by Matthias Meijers at 3rd NIST PQC conference: `https://csrc.nist.gov/Presentations/2021/formal-verifcation-of-post-quantum-cryptography`

Thank you!

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