AND THEN THERE WERE FOUR:
THE FIRST NIST PQC STANDARDS

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National Institute of Standards and Technology
U.S. Department of Commerce

Crypto Technology Group
Computer Security Division
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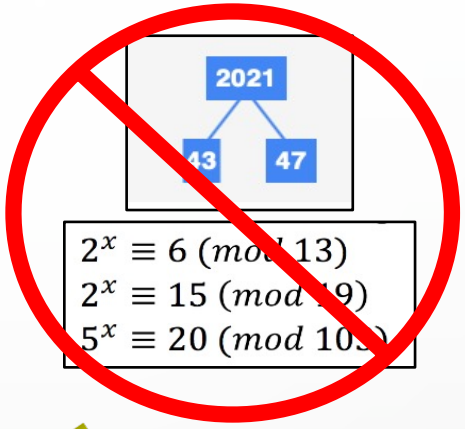
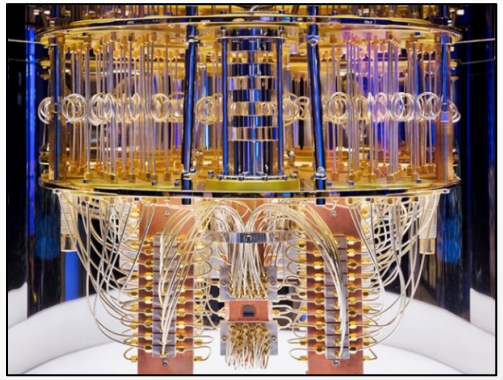
THE QUANTUM THREAT

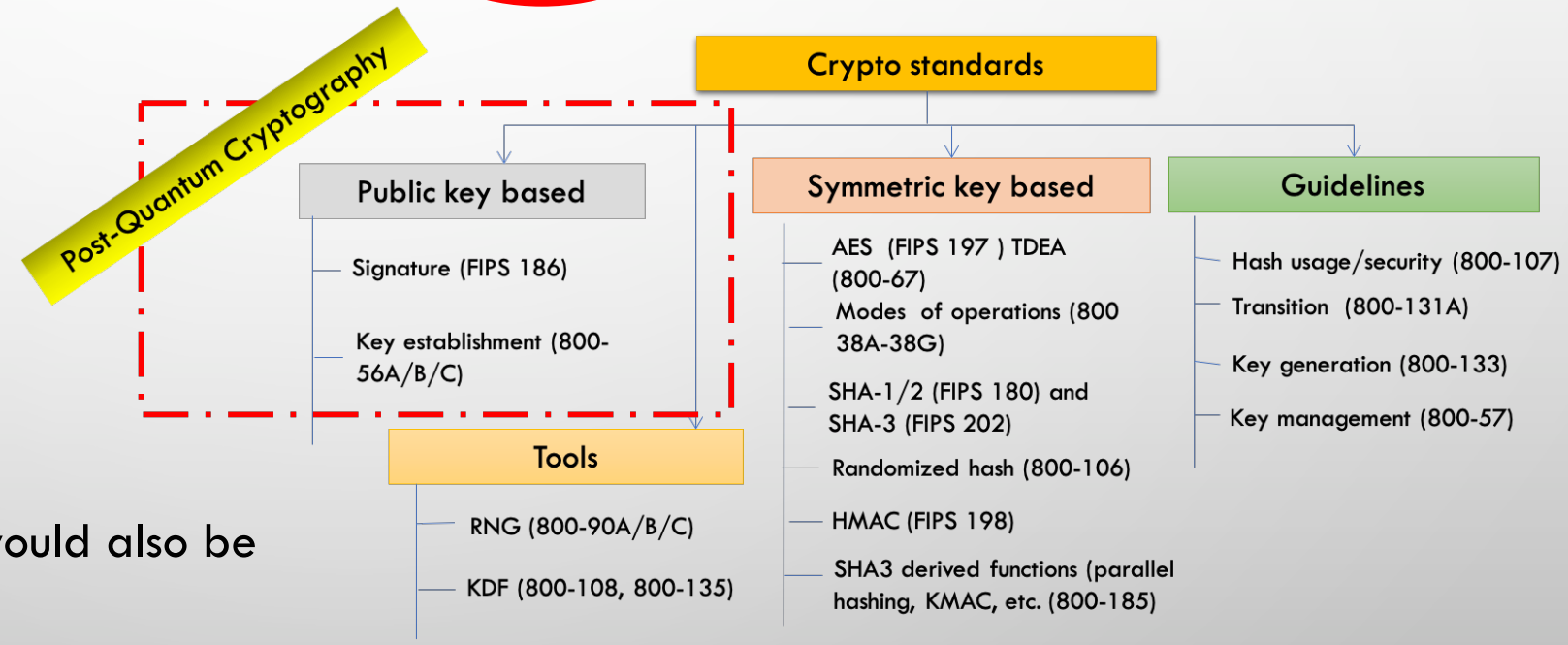
- NIST public-key crypto standards
  - **SP 800-56A**: Diffie-Hellman, ECDH
  - **SP 800-56B**: RSA encryption
  - **FIPS 186**: RSA, DSA, and ECDSA signatures

  all vulnerable to attacks from

  a (large-scale) quantum computer







- Symmetric-key crypto (AES, SHA) would also be affected, but less dramatically

THE PQC "COMPETITION"

- NIST CALLED FOR QUANTUM-RESISTANT CRYPTOGRAPHIC ALGORITHMS FOR NEW PUBLIC-KEY CRYPTO STANDARDS
  - DIGITAL SIGNATURES
  - ENCRYPTION/KEY-ESTABLISHMENT
- OUR ROLE: MANAGING A PROCESS OF ACHIEVING COMMUNITY CONSENSUS IN AN OPEN, TRANSPARENT, AND TIMELY MANNER
- DIFFERENT AND MORE COMPLICATED THAN PAST AES/SHA-3 COMPETITIONS
- THERE WOULD NOT BE A SINGLE "WINNER"
  - IDEALLY, SEVERAL ALGORITHMS WILL EMERGE AS 'GOOD CHOICES'

ROUND 3 RESULTS

3rd round selection (KEM)	3rd round selection (Signatures)
CRYSTALS-Kyber	**CRYSTALS-Dilithium, Falcon, SPHINCS+**

See NISTIR 8413, *Status Report on the 3rd Round of the NIST PQC Standardization Process,* for the rationale on the selections

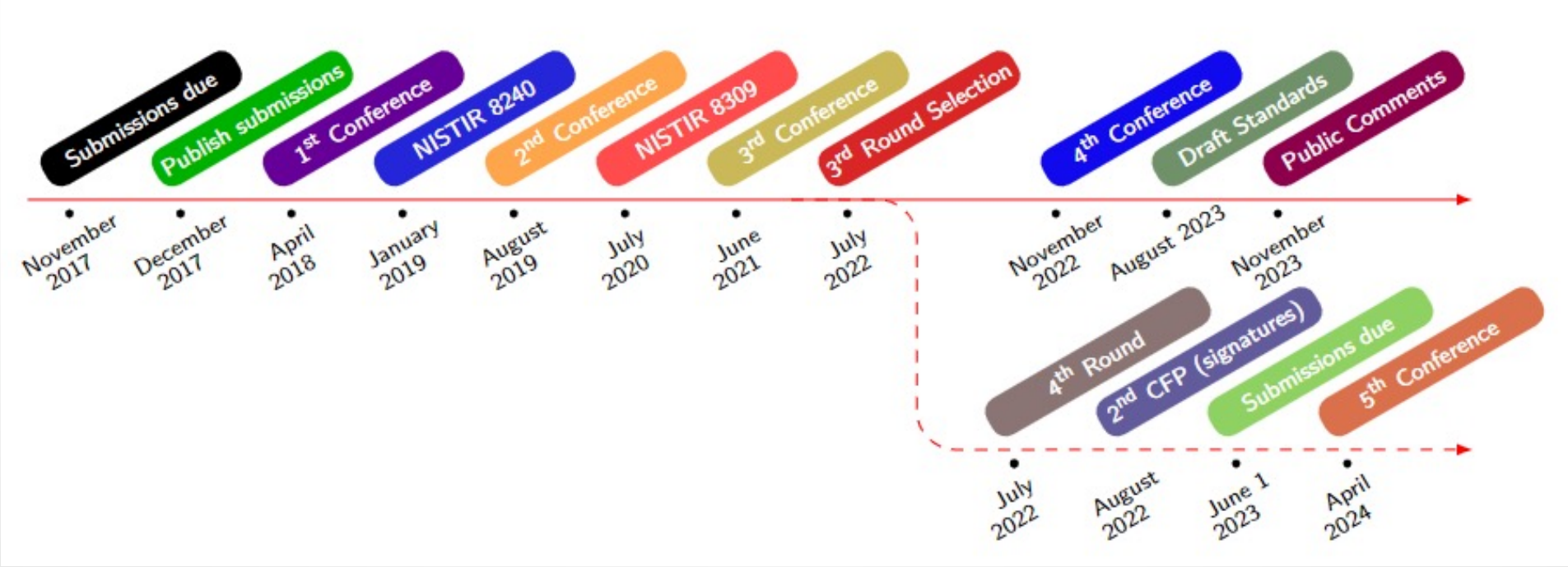
4th round candidates (all KEMs) evaluated for 18-24 months

- ClassicMcEliece
- BIKE
- HQC
- ~~SIKE~~

On-ramp signatures

- NIST issued a new call for additional signatures – preferably for signatures based on non-lattice problems

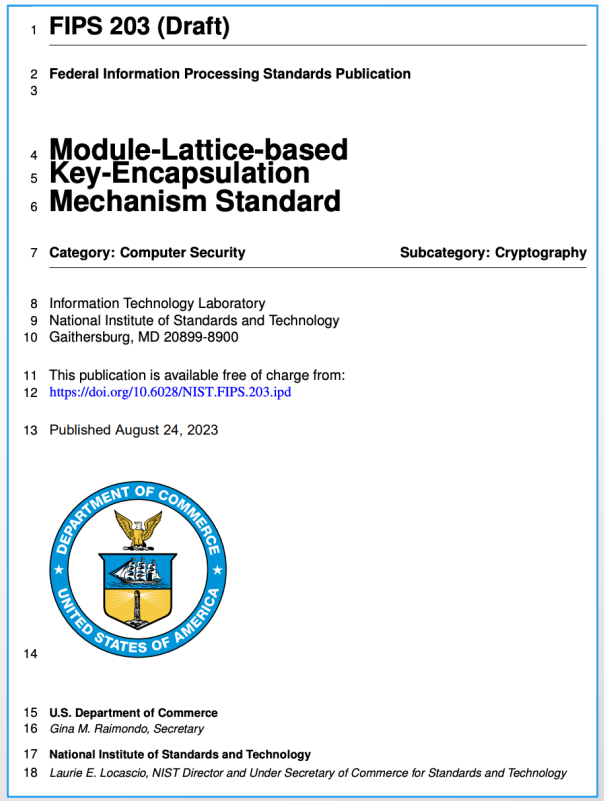
TIMELINE



- The 5th NIST PQC Standardization Conference
  - April 10-12, 2024 in Rockville, Maryland
- Draft standards for public comment released Aug 2023
  - Deadline for comments: November 22, 2023
- **The first PQC standards should be published in 2024**

STANDARDIZATION

- THE 1ST PQC STANDARDS
  - FIPS 203: ML-KEM (KYBER)
  - FIPS 204: ML-DSA (DILITHIUM)
  - FIPS 205: SLH-DSA (SPHINCS+)
  - FN-DSA (FALCON) – UNDER DEVELOPMENT
  - WILL HAVE OTHER DOCS WITH MORE GUIDANCE/DETAILS
- SOME CHOICES MADE
  - WHICH PARAMETER SETS, WHICH HASH FUNCTIONS, OTHER SYMMETRIC PRIMITIVES, ETC
- PLEASE PROVIDE FEEDBACK
  - PQC-FORUM, EMAIL ETC



FIPS 203 (Draft)

Federal Information Processing Standards Publication

Module-Lattice-based Key-Encapsulation Mechanism Standard

Category: Computer Security **Subcategory: Cryptography**

Information Technology Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899-8900

This publication is available free of charge from:
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Gina M. Raimondo, Secretary

National Institute of Standards and Technology
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CRYSTALS-DILITHIUM

NIST

- SIGNATURE BASED ON STRUCTURED LATTICES
- ALL OPERATIONS OVER $R = \mathbb{Z}_q[x]/(x^{256}+1)$

KeyGen:

$A \leftarrow R^{n \times m}$

$s \leftarrow S^m$

$t = \text{Round}(As)$

$pk=(A,t)$ $sk=s$

Sign(pk,sk,μ):

$y \leftarrow Y^m$

$w=\text{Round}(Ay)$

$c=\text{Hash}(w,\mu)$

$z=sc+y$

RejectionSample(pk,sk,z)

$\omega = \text{HintVector}(pk,sk,z)$

$\sigma = (z, \omega, c)$

Verify(μ,σ,pk):

$w=\text{UseHintVector}(pk,\sigma)$

check that $c=\text{Hash}(w, \mu)$ and $|z|$ is small

Slide from Round 3 Dilithium update talk

FALCON

- SIGNATURE BASED ON STRUCTURED LATTICES

We work over the cyclotomic ring $\mathcal{R} = \mathbb{Z}_q[x]/(x^n + 1)$.

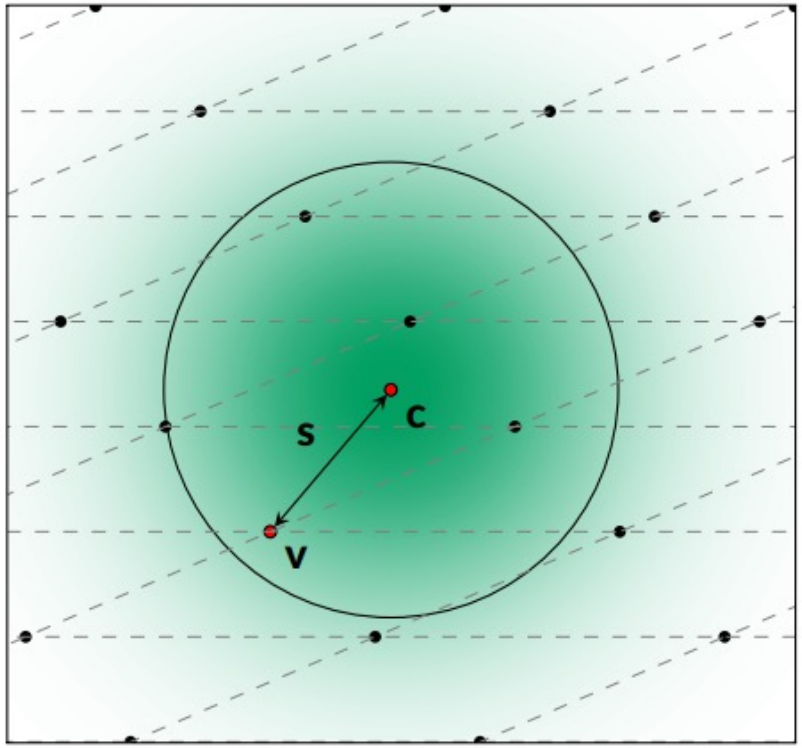
- **Keygen()**
  1. Generate matrices **A**, **B** with coefficients in $\mathcal{R}$ such that
     - $\mathbf{BA} = 0$
     - **B** has small coefficients
  2. pk $\leftarrow$ **A**
  3. sk $\leftarrow$ **B**

- **Sign(m,sk)**
  1. Compute **c** such that $\mathbf{cA} = H(\mathrm{m})$
  2. **v** $\leftarrow$ "a vector in the lattice $\Lambda(\mathbf{B})$, close to **c**"
  3. **s** $\leftarrow \mathbf{c} - \mathbf{v}$

  The signature sig is $\mathbf{s} = (s_1, s_2)$

- **Verify(m,pk sig)**
  Accept iff:
  1. **s** is short
  2. $\mathbf{sA} = H(\mathrm{m})$

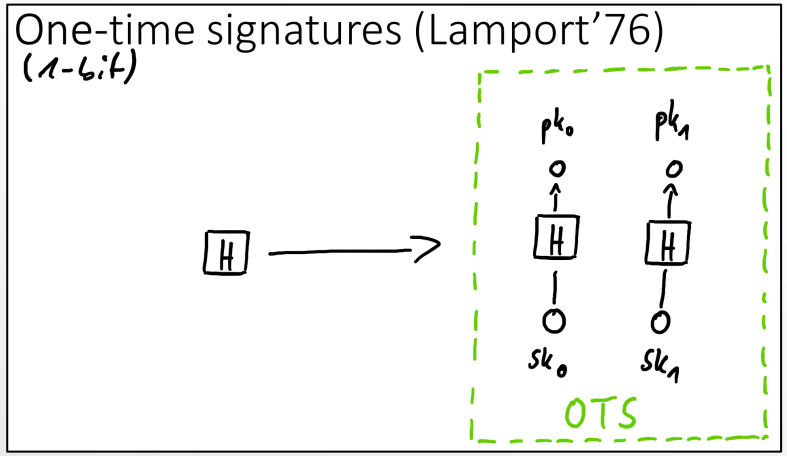
$\Rightarrow$

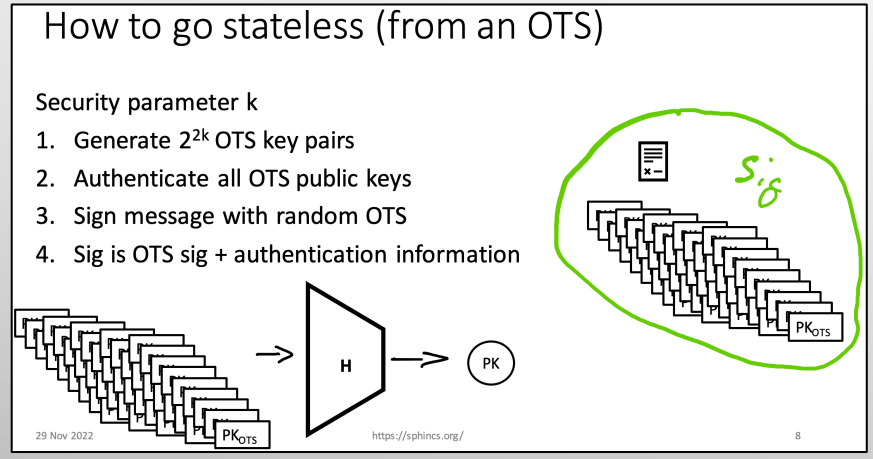


Slide from Round 1 Falcon talk

SPHINCS+

- DIGITAL SIGNATURE BASED ON STATELESS HASH-BASED CRYPTOGRAPHY
- USE ROUND 2 PRESENTATION





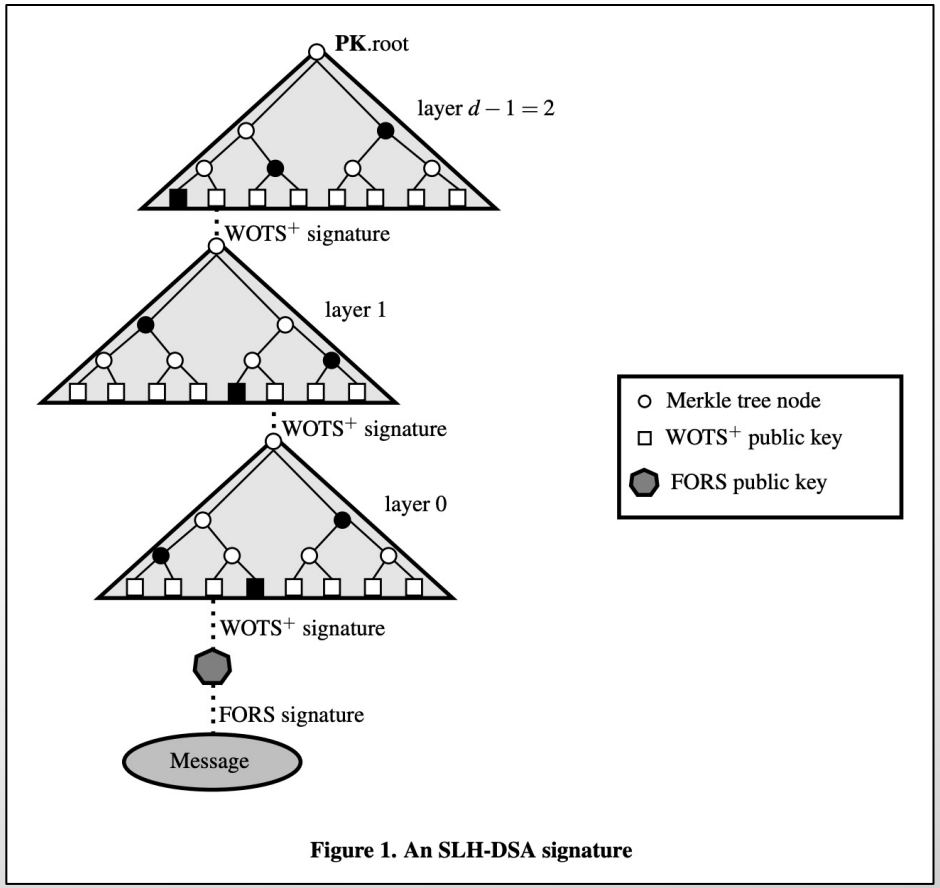


Figure 1. An SLH-DSA signature

Slides from draft FIPS 205 and A. Hulsing's talk at RWPQC 2023

CRYSTALS-KYBER

NIST

- KEM BASED ON STRUCTURED LATTICES
- ALL OPERATIONS OVER $R = \mathbb{Z}_q[x]/(x^n + 1)$

Kyber.CPAPKE: LPR encryption or "Noisy ElGamal"

$\mathbf{A}, \mathbf{s}, \mathbf{e} \leftarrow \chi$ (a Gaussian distribution)

$sk = \mathbf{s}, pk = \mathbf{t} = \mathbf{A}\mathbf{s} + \mathbf{e}$

$\mathbf{r} \leftarrow \chi$

$\mathbf{e}_1, e_2 \leftarrow \chi'$

$\mathbf{u} \leftarrow \mathbf{A}^T\mathbf{r} + \mathbf{e}_1$

$v \leftarrow \mathbf{t}^T\mathbf{r} + e_2 + \mathrm{Enc}(m)$

$c = (\mathbf{u}, v)$

$m = Dec(v - \mathbf{s}^T\mathbf{u})$

Slide from Round 3 Kyber update talk

THE KEMS IN THE 4TH ROUND

- Classic McEliece
  - NIST is confident in the security
  - Smallest ciphertexts, but largest public keys
  - We'd like feedback on specific use cases for Classic McEliece
- BIKE
  - Most competitive performance of 4th round candidates
  - We encourage vetting of IND-CCA security
- HQC
  - Offers strong security assurances and mature decryption failure rate analysis
  - Larger public keys and ciphertext sizes than BIKE
- ~~SIKE~~
  - The SIKE team acknowledges that SIKE (and SIDH) are insecure and should not be used

CONCLUSION

- THE BEGINNING OF THE END IS HERE!
- OR IS IT THE END OF THE BEGINNING?

- WHAT WILL BE THE INTERSECTION OF THE PQC AND THRESHOLD PROJECTS?

- NIST IS GRATEFUL FOR EVERYBODY'S EFFORTS

- CHECK OUT WWW.NIST.GOV/PQCRYPTO
  - SIGN UP FOR THE PQC-FORUM FOR ANNOUNCEMENTS & DISCUSSION
  - SEND E-MAIL TO PQC-COMMENTS@NIST.GOV