NIST PQC Standardization – An Overview

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NIST

NIST Mission:
To promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve our quality of life.

Information Technology Laboratory Mission:
Cultivating trust in IT and metrology.

Computer Security Division Mission:
Conduct research, development and outreach necessary to provide standards and guidelines, mechanisms, tools, metrics and practices to protect information and information systems.

Crypto Technology Group Mission:
Research, develop, engineer, and standardize cryptographic algorithms, methods, and protocols.

NIST Cryptography Program

NIST Cryptography Standards

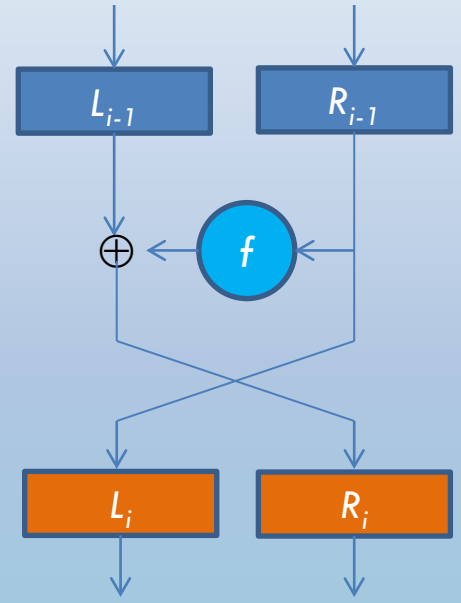
NIST developed the first encryption standards in 1970s, Data Encryption Standards (DES), and published as Federal Information Processing Standard (FIPS) 47

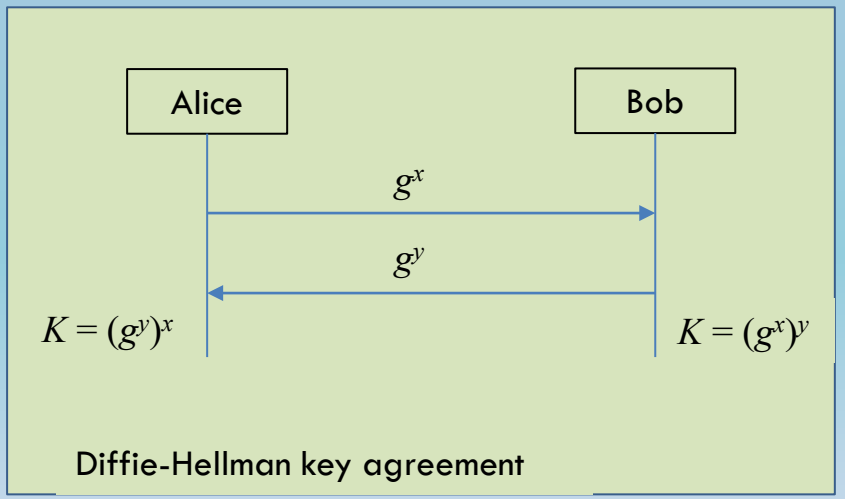
Over 40 years, NIST continues to evolve its cryptographic standards to keep pace with new cryptographic technologies and advanced analysis methods

- 1997-2000 NIST held a block cipher competition and selected a new block cipher algorithm Advanced Encryption Standard (AES), specified in FIPS 197
- 2007-2012 NIST held a hash function competition and selected a hash function named SHA-3 specified in FIPS 202

In late 1980s and beginning of 1990s, NIST started to standardize public key cryptography for Internet and e-commerce needs

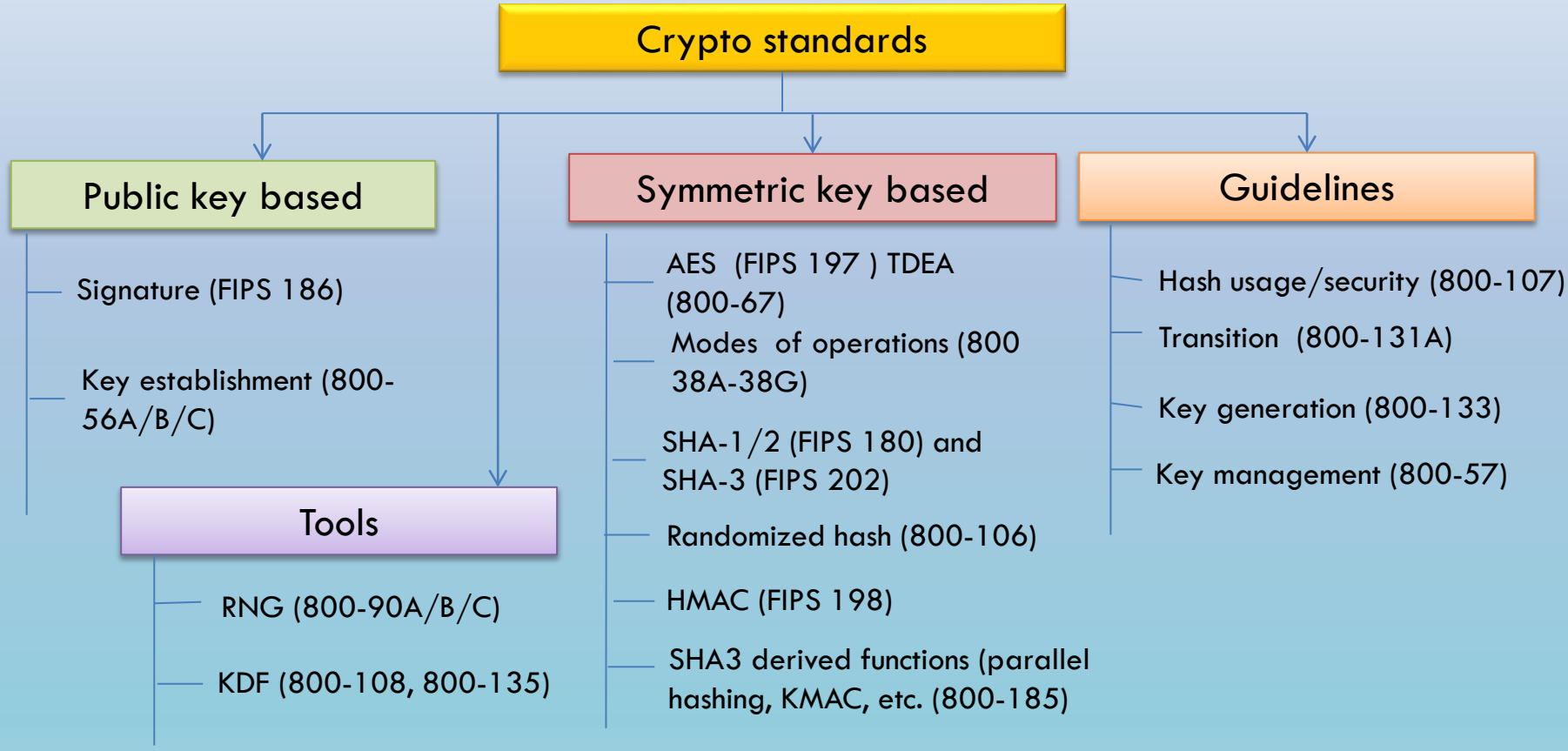
- SP 800-56A (key agreement, e.g. Diffie-Hellman)
- SP 800-56B (RSA based encryption/key transport)
- FIPS 186 (RSA signatures, ECDSA)





Diffie-Hellman key agreement

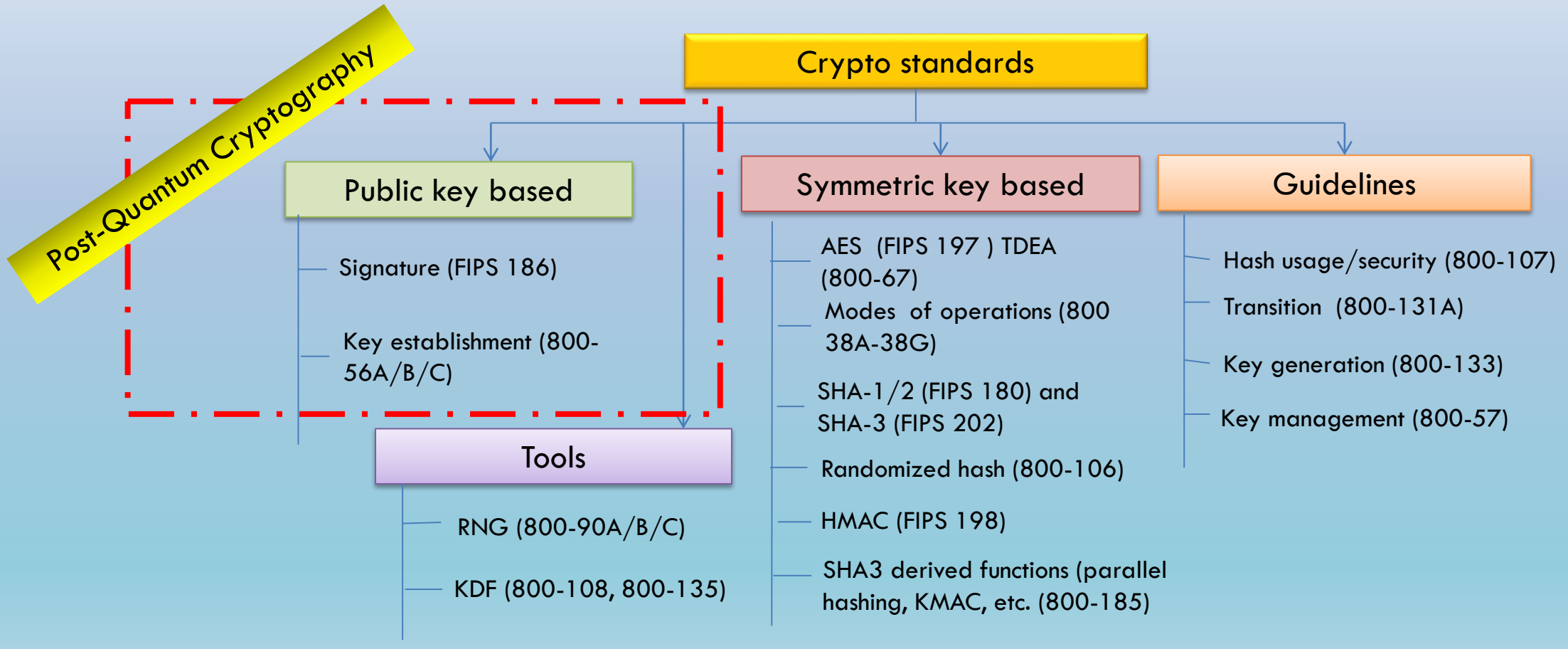
NIST Cryptography Standards



Quantum Impact

- Emerging quantum computers changed what we believed about the hardness of discrete log and factorization problems
  - Using quantum computers, an integer *n* can be factored in polynomial time using Shor's algorithm
  - The discrete logarithm problem can also be solved by Shor's algorithm in polynomial time
- As a result, the public key cryptosystems deployed since the 1980s will need to be replaced
  - RSA signatures, DSA and ECDSA (FIPS 186-4)
  - Diffie-Hellman Key Agreement over finite fields and elliptic curves(NIST SP 800-56A)
  - RSA encryption (NIST SP 800-56B)
- We have to look for quantum-resistant counterparts for these cryptosystems
- Quantum computing also impacted security strength of symmetric key based cryptography algorithms
  - Grover's algorithm can find AES key with approximately $\sqrt{2^n}$ operations where n is the key length
  - Intuitively, we should double the key length, if 2^{64} quantum operations cost about the same as 2^{64} classical operations
    - Based on current understanding about the cost of Grover's attack, we will probably not need such a large key length increase in practice

NIST Post-Quantum Cryptography Standards



NIST PQC Milestones

2009 – NIST Survey paper on Post-Quantum Cryptography

2012 – NIST began PQC project Research and started to build NIST team

April 2015 – 1st NIST PQC workshop

Feb 2016 – NIST Report on PQC (NISTIR 8105)

Feb 2016 – NIST preliminary announcement of standardization plan

Aug 2016 –Dec 2016 – Announcement of finalized requirements and criteria(Federal Register Notice)

Nov. 30, 2017 – Submission deadline, received 82 submissions

Dec. 24, 2017 – Announced the first round 69 algorithms, as “complete and proper”

April 11-13, 2018 – The 1st NIST PQC Standardization Conference (Fort Lauderdale, FL)

January 30, 2019 – Announcement of the 2nd round candidates

August 22-24, 2019 – The 2nd NIST PQC Standardization Conference (Santa Barbara, CA)

Scope

Digital signature

- Replace the schemes specified in FIPS 186-4 (RSA, DSA, ECDSA)

Public Key Encryption/Key Encapsulation

- Replace key establishment specified in
  - SP 800-56A (DH/ECDH, MQV/ECMQV)
  - SP 800-56B (RSA public key secret value transport and encryption OAEP)

The Selection Criteria

Security - against both classical and quantum attacks

Performance - measured on various "classical" platforms

Other properties

- Drop-in replacements - Compatibility with existing protocols and networks
- Perfect forward secrecy
- Resistance to side-channel attacks
- Simplicity and flexibility
- Misuse resistance, and
- More

The draft requirements and criteria were announced in August 2016 to call for public comments

Quantum Security

The comments received on draft requirements and criteria focused on quantum security

- No clear consensus on best way to measure quantum attacks

Uncertainties

- The possibility that new quantum algorithms will be discovered, leading to new attacks
- The performance characteristics of future quantum computers, such as their cost, speed and memory size

For PQC standardization, need to specify concrete parameters with security estimates, that is,

- A selected parameter set maps to a specific security level

Security Strength Categories

Level	Security Description
I	At least as hard to break as AES128 (exhaustive key search)
II	At least as hard to break as SHA256 (collision search)
III	At least as hard to break as AES192 (exhaustive key search)
IV	At least as hard to break as SHA384 (collision search)
V	At least as hard to break as AES256 (exhaustive key search)

Computational resources should be measured using a variety of metrics

NIST asked submitters to focus on levels 1,2, and 3

- Levels 4 and 5 for high security

Security definitions (proofs recommended, but not required) used to judge whether an attack is relevant

- IND-CPA/IND-CCA2 for encryptions and KEMs
- EUF-CMA for signatures

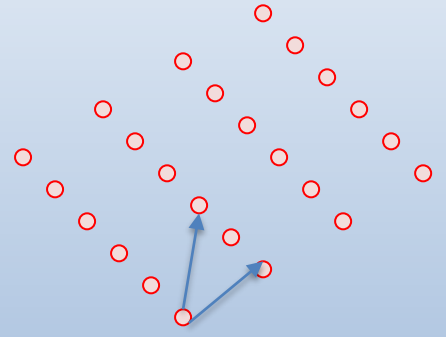
Post-Quantum Cryptography (PQC)

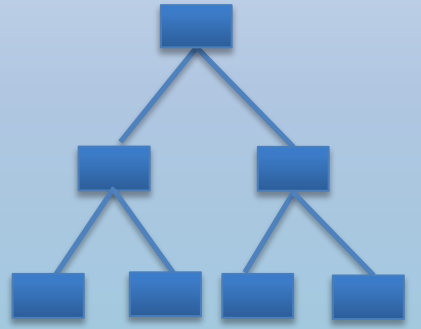
The 1st PQCrypto Conference was held in 2006 in Leuven, Belgium

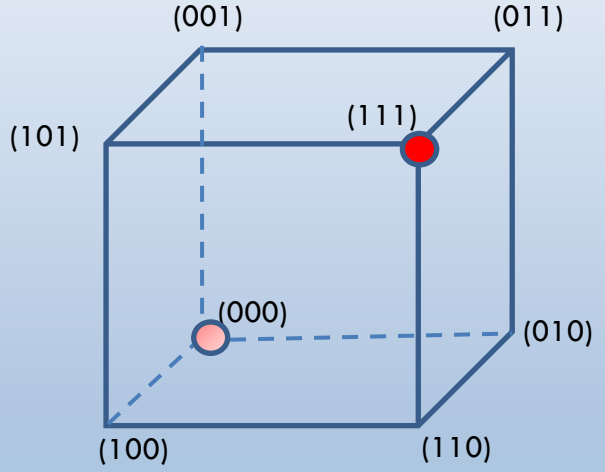
- It has become an annual conference since 2016
- PQC has become a very active research area

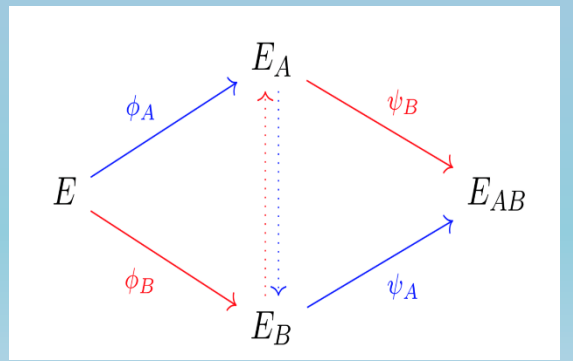
Some actively researched PQC categories

- Lattice-based
- Code-based
- Multivariate
- Hash based signatures
- Isogeny-based schemes









$$p^{(1)}(x_1,\ldots,x_n) = \sum_{i=1}^{n}\sum_{j=i}^{n} p_{ij}^{(1)} \cdot x_i x_j + \sum_{i=1}^{n} p_i^{(1)} \cdot x_i + p_0^{(1)}$$

$$p^{(2)}(x_1,\ldots,x_n) = \sum_{i=1}^{n}\sum_{j=i}^{n} p_{ij}^{(2)} \cdot x_i x_j + \sum_{i=1}^{n} p_i^{(2)} \cdot x_i + p_0^{(2)}$$

$$\vdots$$

$$p^{(m)}(x_1,\ldots,x_n) = \sum_{i=1}^{n}\sum_{j=i}^{n} p_{ij}^{(m)} \cdot x_i x_j + \sum_{i=1}^{n} p_i^{(m)} \cdot x_i + p_0^{(m)}$$

Submissions to NIST Call for Proposals and the 1st Round Candidates

Before submission deadline (Nov. 30, 2017), 82 total submissions received from 25 Countries, 6 Continents

- The submitters in USA are from 16 States

69 accepted as "complete and proper" (5 since withdrawn)

	Signatures	KEM/Encryption	Overall
Lattice-based	5	21	26
Code-based	2	17	19
Multi-variate	7	2	9
Stateless Hash or Symmetric based	3		3
Other	2	5	7
Total	**19**	**45**	**64**

Evaluation of the 1st Round

NIST team held internal seminars to present each candidate to understand how it works, look into security analysis provided by the submitters, raise questions, discuss pros and cons, etc.

Security analysis

- Research publications at conferences and journals (e.g. PQCrypto)
- Official comments - Over 300 official comments in the first round evaluation
- E-mail discussions at pqc-forum – 926 posts

Performance

- Evaluation resources include
  - NIST's internal testing with submitters' code
  - Preliminary benchmarks – SUPERCOP, OpenQuantumSafe, etc.

Selection of 2nd Round Candidates

Security

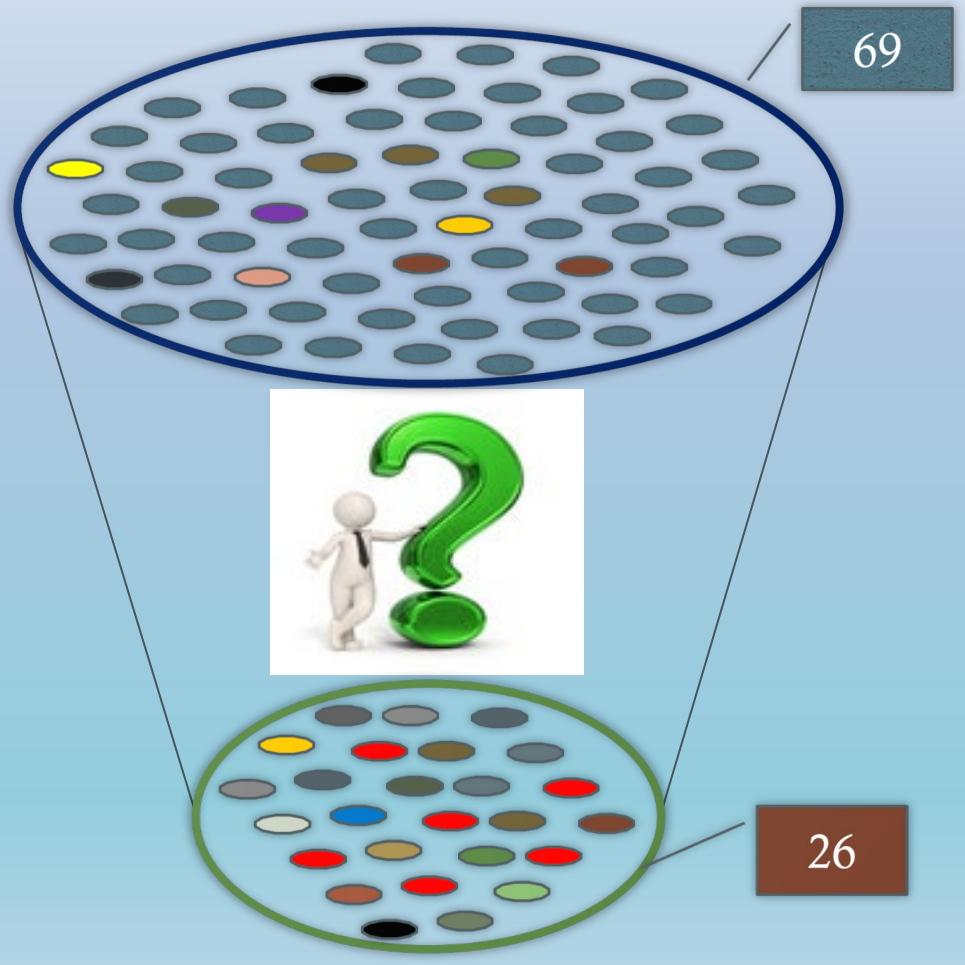
- Candidates which were broken, significantly attacked, or difficult to establish confidence in their security were left out
- Candidates which provided clear design rationale and reasonable security proofs to establish reasonable confidence in security are advanced

Performance

- Candidates with obvious performance or key/signature/ciphertext size issues for existing applications were not advanced - even though they might have been well prepared with good ideas

Diversity

- Candidates with good security and performance were kept if they offered unique security assumptions or performance tradeoffs
- Some candidates were very similar and NIST tried to encourage mergers and advance only the most promising few



The 2nd Round Candidates

We wanted to keep algorithm diversity and promote research, but had to reduce the number of candidates to a manageable size for the community

- It is hard to make comparison among candidates in different categories
- Sometimes even in the same category, it is not always possible to rank them

Some candidates were merged as NIST encouraged

	Signatures	KEM/Encryption	Overall
Lattice-based	3	9	12
Code-based		7	7
Multi-variate	4		4
Stateless Hash or Symmetric based	2		2
Isogeny		1	1
Total	**10**	**16**	**26**

Review of the 2nd Round Candidates

The 2nd round candidates cover algorithms in the most researched categories for post quantum cryptography

In the same category, candidates are designed with different ideas and mathematical structures, e.g.

- Lattice-based includes unstructured LWE, RLWE, MLWE, NTRU using Rounding, Error Correction, etc.
- Code-based includes schemes based on rank metric and Hamming metric, and the original 1979 McEliece cryptosystem based on Goppa codes
- Multivariate signature schemes include the Hidden Field Equations (HFEv-) family and also the Unbalanced Oil Vinegar (UOV) family
- Signature schemes are either in hash-and-sign or in Fiat-Shamir format

The 2nd round includes candidates with relatively conservative approaches as well as more aggressive/optimized designs

The 2nd round candidates provide a full spectrum for investigation

Next Steps - Security

Security proofs – whether the proof is correct

- Security reduction under random oracle model (ROM) and quantum random oracle model (QROM) for IND-CPA or IND-CCA2

Security strength estimation – whether the estimation is precisely close

- Classical security strength is sometimes estimated, e.g. in lattice based schemes, by a combination of theory and heuristics – closer investigations may be needed for more precise estimations
- Quantum security strength is estimated by
  - Quantum algorithms on a specific problem
  - Grover's algorithm to speed up search

Practical security

- Security against side-channel attacks
- Security to deal with decryption failure, incorrect error distribution, improper implementation of auxiliary functions/transitions, etc.

Next Steps - Performance

Benchmarks on different platforms and implementation environments

- For hardware, NIST asks to focus on Cortex M4 (with all options) and Artix-7
  - Researchers also explored Cortex-A53 and UltraScale+ for high performance
  - Identify different speed up technologies and also essential barriers in enabling hardware speed up for specific algorithms
- Performance in software only or limited available hardware environment
- RAM + Flash required for the implementation in constrained environments

Performance in protocols and applications

- Signature verification in secure boot, software update, application authorizations
- Impact of key size on latency for real time protocols like TLS and IKE

Power consumption and other costs

- Get more precise estimation

Next Steps - Transition

Enable crypto agility for public key encryption/key encapsulation, signature

- Allow introduction of new algorithms in existing applications and removal of algorithms vulnerable to attacks, classical and/or quantum
- Assess implementation costs and required bandwidth/space
- Adapt protocols and applications to accommodate new algorithms

Understand tradeoff preferences in each application

- Identify restrictions, limitations, and show stoppers

Gain first-hand experience through trial implementations

- Eliminate security pitfalls and explore implementation optimizations

Introduce hybrid mode and/or dual signature in the current protocols and applications

- Prevent crashing from single security failure

Timeline

Spend 12-18 months to analyze and evaluate the 2nd round candidates

Announce the 3rd round candidates in June 2020

Hold the 3rd NIST PQC Standardization Conference in winter 2020 or early 2021

Release draft standards in 2022-2023 for public comments

Summary – Road ahead

We will have many decisions to make

- When can we tell the security analysis is sufficient?
- Shall we start from the most conservative algorithms?
- How much to weigh security proofs?
- When shall we finalize the standards?

We will continue open for suggestions and encourage discussions

- For NIST PQC project, please follow us at

  https://www.nist.gov/pqcrypto
- To submit a comment, send e-mail to pqc-comments@nist.gov
- Join discussion mailing list pqc-forum@nist.gov