

**From:** [Moody, Dustin \(Fed\)](#)  
**To:** [Liu, Yi-Kai \(Fed\)](#); [Alperin-Sheriff, Jacob \(Fed\)](#); [daniel-c.smith@louisville.edu](mailto:daniel-c.smith@louisville.edu)  
**Subject:** Fw: Status update on PQC CFP  
**Date:** Thursday, October 20, 2016 8:39:14 AM  
**Attachments:** [final CFP v3 Ray.docx](#)

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Attached are Ray's edits. 4.A.6 is still in there, although we will take it out and put it in the FAQ. Let me know if you think it's good, or if you have more suggestions/comments. Thanks,

Dustin

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**From:** Perlner, Ray (Fed)  
**Sent:** Wednesday, October 19, 2016 5:02 PM  
**To:** Moody, Dustin (Fed)  
**Subject:** RE: Status update on PQC CFP

Here are my proposed edits. The track changes does not appear to be distinguishing my new edits from previous text I provided, so I've tried to mark my changes in the comments.

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**From:** Moody, Dustin (Fed)  
**Sent:** Wednesday, October 19, 2016 1:51 PM  
**To:** Perlner, Ray (Fed) <[ray.perlner@nist.gov](mailto:ray.perlner@nist.gov)>  
**Subject:** RE: Status update on PQC CFP

Ray,

Please use the attached file for when you make your next edits. Remember to add something about the standard conversion between KEMs and PK encryption schemes. Take a look at any comments that are still there. Remember to add stuff in about doing classical cryptanalysis, independent of anything quantum, and modify the text in 4.A.5 a bit to reflect this emphasis.

Thanks!

Dustin

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**From:** Perlner, Ray (Fed)  
**Sent:** Tuesday, October 18, 2016 10:45 AM  
**To:** Moody, Dustin (Fed) <[dustin.moody@nist.gov](mailto:dustin.moody@nist.gov)>  
**Subject:** RE: Status update on PQC CFP

I have addressed the requested changes on page 19 and in 4.B.3, 4.B.4 and 4.C.1 . I also added a parenthetical "(e.g. AES 256)" in section 4.A.5, for consistency.

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**From:** Moody, Dustin (Fed)  
**Sent:** Tuesday, October 18, 2016 10:01 AM  
**To:** Perlner, Ray (Fed) <[ray.perlner@nist.gov](mailto:ray.perlner@nist.gov)>  
**Subject:** RE: Status update on PQC CFP

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**From:** Perlner, Ray (Fed)  
**Sent:** Monday, October 17, 2016 4:27 PM

**To:** Moody, Dustin (Fed) <[dustin.moody@nist.gov](mailto:dustin.moody@nist.gov)>; Ray Perlner (b) (6); Alperin-Sheriff, Jacob (Fed) <[jacob.alperin-sheriff@nist.gov](mailto:jacob.alperin-sheriff@nist.gov)>; Bassham, Lawrence E (Fed) <[lawrence.bassham@nist.gov](mailto:lawrence.bassham@nist.gov)>; Chen, Lily (Fed) <[lily.chen@nist.gov](mailto:lily.chen@nist.gov)>; Daniel Smith-Tone <[daniel-c.smith@louisville.edu](mailto:daniel-c.smith@louisville.edu)>; Jordan, Stephen P (Fed) <[stephen.jordan@nist.gov](mailto:stephen.jordan@nist.gov)>; Liu, Yi-Kai (Fed) <[yi-kai.liu@nist.gov](mailto:yi-kai.liu@nist.gov)>; Miller, Carl A. (Fed) <[carl.miller@nist.gov](mailto:carl.miller@nist.gov)>; Peralta, Rene (Fed) <[rene.peralta@nist.gov](mailto:rene.peralta@nist.gov)>; Smith-Tone, Daniel (Fed) <[daniel.smith@nist.gov](mailto:daniel.smith@nist.gov)>

**Subject:** RE: Status update on PQC CFP

I have added text for the following purposes

To provide separate security model sections for IND-CCA2 and IND-CPA

To uniformly use the standard terminology for KEMs in place of previous text about “key exchange”

To address Yi-Kai and Jacob’s requests that we explicitly say we aren’t requiring submitters to provide distinct parameters in each of the five security categories, and that we provide a translation table between our security categories and gate counts.

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**From:** Moody, Dustin (Fed)

**Sent:** Wednesday, October 12, 2016 1:27 PM

**To:** Ray Perlner (b) (6); Alperin-Sheriff, Jacob (Fed) <[jacob.alperin-sheriff@nist.gov](mailto:jacob.alperin-sheriff@nist.gov)>; Bassham, Lawrence E (Fed) <[lawrence.bassham@nist.gov](mailto:lawrence.bassham@nist.gov)>; Chen, Lily (Fed) <[lily.chen@nist.gov](mailto:lily.chen@nist.gov)>; Daniel Smith-Tone <[daniel-c.smith@louisville.edu](mailto:daniel-c.smith@louisville.edu)>; Jordan, Stephen P (Fed) <[stephen.jordan@nist.gov](mailto:stephen.jordan@nist.gov)>; Liu, Yi-Kai (Fed) <[yi-kai.liu@nist.gov](mailto:yi-kai.liu@nist.gov)>; Miller, Carl A. (Fed) <[carl.miller@nist.gov](mailto:carl.miller@nist.gov)>; Moody, Dustin (Fed) <[dustin.moody@nist.gov](mailto:dustin.moody@nist.gov)>; Peralta, Rene (Fed) <[rene.peralta@nist.gov](mailto:rene.peralta@nist.gov)>; Perlner, Ray (Fed) <[ray.perlner@nist.gov](mailto:ray.perlner@nist.gov)>; Smith-Tone, Daniel (Fed) <[daniel.smith@nist.gov](mailto:daniel.smith@nist.gov)>

**Subject:** Status update on PQC CFP

Everyone,

Thanks for everybody’s time and effort to finalize our CFP. Here’s a few notes and assignments following our second internal meeting yesterday.

think we resolved most of the minor comments, which have been reflected in the attached updated CFP. Please review it. The changes are marked and easy to see. Let me within a week if anybody sees something that needs to be addressed/fixed.

arry and Ray have written some new FAQ questions. See the attached. I will have Sara post them to the FAQ section next week, unless I hear anything back from anyone. Daniel is going to write one on how our process is different than a competition.

arry is working on resolving the API comments. For some of that, he will work with Ray. Also need to make sure how we change our key-exchange/KEM stuff is reflected in the API.

i-Kai will work with Ray to revise the security section (4.A.4). Yesterday, we agreed with Yi-Kai that it might be best to remove security levels 2 and 4. Possibly discuss this on the pqc-forum.

acob will work with Ray to re-write the portions of the CFP dealing with key-exchange. We agreed to add an ephemeral version. Jacob has suggested some text for 4.A.2, which could be split into 2 sections. They also need to look at 2.B.1 and section 3. We need to agree on our terminology. Would probably also be good to discuss on the pqc-forum.

We had a meeting with the NIST lawyers. They said we need to keep our IPR statements as they currently are (meaning we can't have only royalty free algorithms). There will probably be a few lines added into the CFP strengthening our language that we have a strong preference for royalty-free, and that it will be used as an evaluation criteria. Andy would also like to add a line that we will commit to having at least one algorithm of each type be royalty-free.

We will need to have a 2<sup>nd</sup> FRN announcing our final version of the CFP, but it will be very short, just pointing to our webpage. We will also want to have a short report which summarizes the comments received (text of the comments will also be published), and the main changes we made as a result.

We will have a meeting next Wednesday (10/19), 10am til noon. The main topics of discussion will be the above items.

Thanks!

Dustin

# Proposed Submission Requirements and Evaluation Criteria for the Post-Quantum Cryptography Standardization Process

## Table of Contents

1. Background
2. Proposed Requirements for Submission Packages
  - 2.A Cover Sheet
  - 2.B Algorithm Specifications and Supporting Documentation
  - 2.C Digital and Optical Media
  - 2.D Intellectual Property Statements / Agreements / Disclosures
  - 2.E General Submission Requirements
  - 2.F Technical Contacts and Additional Information
3. Proposed Minimum Acceptability Requirements
4. Proposed Evaluation Criteria
  - 4.A Security
  - 4.B Cost
  - 4.C Algorithm and Implementation Characteristics
5. Proposed Plans for the Evaluation Process
  - 5.A Overview
  - 5.B Technical Evaluation
  - 5.C Initial Planning for the first Post-Quantum Cryptography Standardization Conference

**Authority:** This work is being initiated pursuant to NIST’s responsibilities under the Federal Information Security Management Act (FISMA) of 2002, Public Law 107–347.

## 1. Background

In recent years, there has been a substantial amount of research on quantum computers – machines that exploit quantum mechanical phenomena to solve mathematical problems that are difficult or intractable for conventional computers. If large-scale quantum computers are ever built, they will compromise the security of many commonly used cryptographic algorithms.

In particular, quantum computers would completely break many public-key cryptosystems, including RSA, DSA, and elliptic curve cryptosystems. These cryptosystems are used to implement digital signatures and key establishment and play a crucial role in ensuring the confidentiality and authenticity of communications on the Internet and other networks.

Due to this concern, many researchers have begun to investigate *post-quantum* cryptography (PQC) (also called *quantum-resistant* or *quantum-safe* cryptography). The goal of this research is to develop cryptographic algorithms that would be secure against both quantum and classical computers. These algorithms could serve as replacements for

our current public-key cryptosystems to prepare for the event that large-scale quantum computers become a reality.

At present, there are several post-quantum cryptosystems that have been proposed, including lattice-based cryptosystems, code-based cryptosystems, multivariate cryptosystems, hash-based signatures, and others. However, for most of these proposals, further research is needed in order to gain more confidence in their security (particularly against adversaries with quantum computers) and to improve their performance.

NIST has decided that it is prudent to begin developing standards for post-quantum cryptography now. This is driven by two factors. First, there has been noticeable progress in the development of quantum computers, including theoretical techniques for quantum error correction and fault-tolerant quantum computation, and experimental demonstrations of physical qubits and entangling operations in architectures that have the potential to scale up to larger systems.

Second, it appears that a transition to post-quantum cryptography will not be simple as there is unlikely to be a simple “drop-in” replacement for our current public-key cryptographic algorithms. A significant effort will be required in order to develop, standardize, and deploy new post-quantum cryptosystems. In addition, this transition needs to take place well before any large-scale quantum computers are built, so that any information that is later compromised by quantum cryptanalysis is no longer sensitive when that compromise occurs. Therefore, it is desirable to plan for this transition early.

NIST is beginning a process to develop new post-quantum-resistant cryptography standards to replace existing NIST standards, including digital signature schemes specified in Federal Information Processing Standards Publication (FIPS) 186 and key establishment schemes specified in NIST Special Publications (SP) 800-56 A and B. The process is referred to as post-quantum cryptography standardization. The standards will be published as Federal Information Processing Standards (FIPSs) or Special Publications (SPs).

NIST is soliciting proposals for post-quantum cryptosystems and it will solicit comments from the public as part of its evaluation process. NIST expects to perform multiple rounds of evaluation, over a period of three to five years. The goal of this process is to select a number of acceptable candidate cryptosystems for standardization.

NIST anticipates that the evaluation process for these post-quantum cryptosystems may be significantly more complex than the evaluation of the SHA-3 and AES candidates. One reason is that the requirements for public-key encryption and digital signatures are more complicated. Another reason is that the current scientific understanding of the power of quantum computers is far from comprehensive. Finally, some of the candidate post-quantum-resistant cryptosystems may have completely different design attributes and mathematical foundations, so that a direct comparison of candidates would be difficult or impossible.

As a result of these complexities, NIST believes that its post-quantum standards development process should not be treated as a competition; in some cases, it may not be possible to make a well-supported judgment that one candidate is “better” than another. Rather, NIST will perform a thorough analysis of the submitted algorithms in a manner that is open and transparent to the public, as well as encourage the cryptographic community to also conduct analyses and evaluation. This combined analysis will inform NIST’s decision on the subsequent development of post-quantum standards.

NIST recognizes that some users may wish to deploy systems that use “hybrid modes,” which combine ~~post-quantum-resistant~~ cryptographic algorithms with existing cryptographic algorithms (which may not be ~~post-quantum-resistant~~). These “hybrid modes” are outside of the scope of this document, which is focused on ~~post-quantum-resistant~~ cryptographic algorithms only.

## 2. Proposed Requirements for the Submission Packages

Submission packages must be received by NIST by November 30, 2017. Submission packages received before September 30, 2017 will be reviewed for completeness by NIST; the submitters will be notified of any deficiencies by October 31, 2017, allowing time for deficient packages to be amended by the submission deadline. No amendments to packages will be permitted after the submission deadline, except at specified times during the evaluation phase (see Section 5).

Due to the specific requirements of the ~~submission package, such as the~~ intellectual property statements as specified in Section 2.D, e-mail submissions will not be accepted for these statements ~~or for the initial submission package. However, e-mail submissions of amendments to the initial submission package will be allowed prior to the submission deadline. The statements specified in Section 2.D must be mailed to Dustin Moody, Information Technology Laboratory, Attention: Post-Quantum Cryptographic Algorithm Submissions, 100 Bureau Drive – Stop 8930, National Institute of Standards and Technology, Gaithersburg, MD 20899-8930, or can be given to NIST at the first PQC Standardization Conference (see Section 5.C). The remainder of the submission package can either be mailed with the intellectual property statements, or sent as email to the address: pqc-submissions@nist.gov.~~

“Complete and proper” submission packages will be posted at <http://www.nist.gov/pqcrypto> for review. To be considered as a “complete” submission, packages must contain the following:

- Cover Sheet.
- Algorithm Specifications and Supporting Documentation.
- Optical Media.
- Intellectual Property Statements / Agreements / Disclosures.

These requirements are detailed below.

To be considered as a “proper” submission, packages must meet the minimum acceptability requirements specified in Section 3.

## 2.A Cover Sheet

The cover sheet of a submission package shall contain the following information:

- Name of the proposed cryptosystem.
- Principal submitter’s name, e-mail address, telephone, organization, and postal address.
- Name(s) of auxiliary submitter(s).
- Name of the inventor(s)/ developer(s) of the cryptosystem.
- Name of the owner, if any, of the cryptosystem (normally expected to be the same as the submitter).
- Signature of the submitter.
- (optional) Backup point of contact (with telephone, fax, postal address, and e-mail address).

## 2.B Algorithm Specifications and Supporting Documentation

Each submission must include:

- 1) a complete written specification
- 2) a detailed performance analysis
- 3) Known Answer Test values
- 4) a thorough description of the expected security strength
- 5) an analysis of the algorithm with respect to known attacks
- 6) a statement of advantages and limitations.

Further details are described below.

### 2.B.1

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

Each submission package shall describe a collection of algorithms, also called a cryptosystem or cryptographic scheme, that implements one or more of the following functionalities: public-key encryption, key encapsulation mechanism<sup>1</sup> (KEM), and digital signature. Public-key encryption schemes shall include algorithms for key generation, encryption, and decryption. KEM schemes shall include algorithms for key generation, encapsulation, and decapsulation. Digital-signature schemes shall include algorithms for key generation, signature generation and signature verification.

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<sup>1</sup> In SP 800-56B, Recommendation for Pair-Wise Key Establishment Schemes Using Integer Factorization Cryptography, KEMs are noted to be schemes, and are not to be considered protocols.

~~Each submission package shall describe a collection of algorithms, also called a cryptosystem or cryptographic scheme, that implements one or more of the following functionalities: public key encryption, key establishment, and digital signatures. Public key encryption schemes shall include algorithms for key generation, encryption, and decryption. Key establishment schemes shall include algorithms for generating initiator and responder key establishment messages, as well as algorithms for both initiator and responder to recover a shared secret. Digital signature schemes shall include algorithms for key generation, signature generation and signature verification.~~

If a submission includes more than one type of scheme, NIST will evaluate the schemes of each type separately. Submitters may choose to combine different types of schemes into a single submission. They may also instead prepare and submit a complete submission package for each algorithm, making sure to include all supporting documents and intellectual property statements in each individual package. As the KEM and public key encryption functionalities can generally be interconverted, unless the submitter specifies otherwise, NIST will apply standard conversion techniques to public key encryption algorithms, so that the resulting scheme can be considered for standardization as a KEM, and vice versa: To convert a public key encryption function to a KEM, NIST will construct the encapsulate function by generating a random key and encrypting it. (The key generation and decapsulation functions of the KEM will be the same as the key generation and decryption functions of the original public key encryption scheme.) To convert a KEM to a public key encryption scheme, NIST will construct the encryption function, by appending to the KEM ciphertext, an AES-GCM ciphertext of the plaintext message, with a randomly generated IV. The AES key will be the symmetric key output by the encapsulate function. (The key generation function will be identical to that for the original KEM, and the decryption function will be constructed by decapsulation followed by AES decryption.)

For algorithms that have tunable parameters (such as the dimension of some underlying vector space, or the number of equations and variables), the submission document shall specify concrete values for these parameters. If possible, the submission should specify several parameter sets that allow the selection of a range of possible security/performance tradeoffs. In addition, the submitter should provide an analysis of how the security and performance of the algorithms depend on these parameters. To facilitate the analysis of these algorithms by the cryptographic community, submitters are encouraged to also specify parameter sets that provide lower security levels, and to provide concrete examples that demonstrate how certain parameter settings affect the feasibility of known cryptanalytic attacks.

Specific parameter sets may permit NIST to select a different performance/security tradeoff than originally specified by the submitter, in light of discovered attacks or other analysis, and in light of the alternative algorithms that are available. NIST will consult with the submitter of the algorithm, as well as the cryptographic community, if it plans to select that algorithm for development as a NIST standard, but with a different parameter set than originally specified by the submitter.

Commented [PR(1)]: Maybe specify this in the API document?

DM: We decided to just do it here.

RP: See added text. I still think we should put this in code somewhere.



A complete submission shall specify any padding mechanisms and any uses of NIST-approved cryptographic primitives that are needed in order to achieve security. If the scheme uses a cryptographic primitive that has not been approved by NIST, the submitter shall provide an explanation for why a NIST-approved primitive would not be suitable.

To help rule out the existence of possible back-doors in an algorithm, the submitter shall explain the provenance of any constants or tables used in the algorithm.

**2.B.2** The submitter must also include a statement regarding the algorithm’s estimated computational efficiency and memory requirements for the “NIST PQC Reference Platform” (specified in Section 5.B). Efficiency estimates for other platforms may be included at the submitter’s discretion. These estimates shall each include the following information, at a minimum:

- a. A description of the platform used to generate the estimate, in sufficient detail so that the estimates could be verified in the public evaluation process. For software implementations, include information about the processor, clock speed, memory, and operating system, on which the performance estimates were obtained. For hardware estimates, a gate count (or estimated gate count) should be included.
- b. A speed estimate and memory requirements for the algorithm(s) on the reference platform specified in Section 5.B. At a minimum, the number of milliseconds or clock cycles required to perform each required operation (e.g., key generation, encryption, decryption, sign, verify), and the size of all inputs and outputs (e.g., keys, ciphertexts, signatures).

**2.B.3** In addition, each submission package is required to include Known Answer Test (KAT) values that can be used to determine the correctness of an implementation of the submitted algorithms. The KATs are individual input tuples that produce single output values, e.g., an input tuple of a key and plaintext resulting in an output of the corresponding ciphertext. If an algorithm uses random values, the KAT should specify a fixed value for the random bits used by the algorithm, in order to force the algorithm to produce a fixed output value. Separate KATs should be provided to test different aspects of the algorithm, e.g., key generation, encryption, decryption, sign, verify, etc.

The KATs shall be included as specified below. All of these KAT values shall be submitted electronically, in separate files, on a CD-ROM, DVD, USB flash drive, or included in a zip file as described in Section 2.C.4.

Each file must be clearly labeled with header information listing:

1. Algorithm name,
2. Test name,
3. Description of the test, and
4. Other parameters.

The list must be followed by a set of tuples where all values within the tuple are clearly labeled (e.g., Plaintext, PublicKey, RandomBits, Ciphertext, etc.). Sample files for these KAT values will be posted at <http://www.nist.gov/pqcrypto>.

All applicable KATs that can be used to verify various features of the algorithm shall be included. A set of KATs shall be included for each security strength specified in Section 4.A. Required KATs include:

- a) If the execution of an algorithm produces intermediate results that are informative (e.g., for debugging an implementation of the algorithm), then the submitter shall include known answers for those intermediate values for each of the required security strengths. Examples of providing such intermediate values are available at: <http://csrc.nist.gov/groups/ST/toolkit/index.html>.
- b) If tables are used in an algorithm, then a set of KAT vectors shall be included to make use of the table entries.

**Note:** The submitter is encouraged to include any other KATs that test different features of the algorithm (e.g., for permutation tables, padding scheme, etc.). The purposes of these tests shall be clearly described in the file containing the test values.

2.B.4 The submission package shall include a statement of the expected security strength of the cryptosystem, along with a supporting rationale. For each parameter set the submitter wishes NIST to consider for standardization, the submitter shall specify a security model from sections 4.A.2, 4.A.3, and/or 4.A.4, as well as an estimated security strength according to the categories given in section 4.A.5. All submitters are advised to be somewhat conservative in assigning parameters to a given category, but submitters of algorithms where the complexity of the best known attack has recently decreased significantly, or is otherwise poorly understood, should be especially conservative. Submitters should give quantitative estimates for any additional security provided by their settings above and beyond the minimum security strength provided by the relevant security strength category. Such estimates should include, at a minimum, a claimed classical security strength. Furthermore, the statement should address the additional attack scenarios identified in Section 4.A.7.

~~The submission package shall include a statement of the expected security strength of the cryptosystem, along with a supporting rationale. For each parameter set, the submitter should specify a corresponding security target from Section 4.A.4 and at least one security model from Sections 4.A.2 and 4.A.3. The parameters should be chosen so that the submitter is confident that the specified security target is met or exceeded. If the submitter believes that these settings exceed the relevant security target, the submitter shall give an estimate of how much the settings will exceed the security target. Furthermore, the statement should address the additional attack scenarios identified in Section 4.A.5.~~

Commented [PR(2)]: This was a "should", I think this should be a "shall"

Commented [PR(3)]: Note the added sentence.

**2.B.5** The submission package shall include a statement that summarizes the known cryptanalytic attacks on the scheme, and provides estimates of the complexity of these attacks.

The submitter shall provide a list of references to any published materials describing or analyzing the security of the submitted algorithm or cryptosystem. When possible, the submission of copies of these materials (accompanied by a waiver of copyright or permission from the copyright holder for public evaluation purposes) is encouraged.

**2.B.6** The submission package shall include a statement that lists and describes the advantages and limitations of the cryptosystem. Such advantages and limitations may involve the assessment of the cryptosystem's security against classical and quantum attacks, as well as any unusual characteristics of the scheme, such as extra functionalities, performance tradeoffs, and unusual vulnerabilities. This statement may also discuss the ease of implementing and deploying the algorithms, and their compatibility with existing protocols, networks and applications. This could include, for example, the suitability of the algorithm for use in hybrid schemes, which may be part of the transition to post-quantum cryptosystems.

In addition, this statement may address the ability to implement the algorithms in various environments, including, but not limited to 8-bit processors (e.g., smartcards), voice applications, satellite applications, or other environments where low power, constrained memory, or limited real-estate are consideration factors. To demonstrate the efficiency of a hardware implementation of the algorithm, the submitter may include a specification of the algorithm in a nonproprietary hardware description language (HDL).

## **2.C Digital and Optical Media**

All electronic data shall be provided either in a zip file, or on a single CD-ROM, DVD, or USB flash drive labeled with the submitter's name, as well as the name of the proposed cryptosystem.

**2.C.1 Implementations** Two implementations are required in the submission package: a reference implementation and an optimized implementation. The goal of the reference implementation is to promote understanding of how the submitted algorithm may be implemented. Since this implementation is intended for reference purposes, clarity in the implementation code is more important than the efficiency of the code. The reference implementation should include appropriate comments and clearly map to the algorithm description included in Section 2.B.1. The optimized implementation, targeting the Intel x64 processor (a 64-bit implementation), is intended to demonstrate the performance of the algorithm. Both implementations shall consist of source code written in ANSI C.

Both implementations shall be capable of fully demonstrating the operation of the proposed algorithm. This includes support for all core features of the algorithm, e.g., encryption, decryption, key generation, public-key validation, shared secret generation, and digital signature generation and verification.

A separate document specifying a set of cryptographic service calls, i.e. a cryptographic API, for the ANSI C implementations, will be made available at <http://www.nist.gov/pqcrypto>. Both the reference implementation and the optimized implementation shall adhere to the provided API. Separate source code for implementing the KATs shall also be included and shall adhere to the provided API.

The reference implementation shall be provided in a directory labeled: Reference\_Implementation.

The optimized implementation shall be provided in a directory labeled: Optimized\_Implementation.

Submitters may, at their discretion, submit additional implementations for other platforms. These implementations may be useful during the evaluation process.

**2.C.2 Known Answer Tests** The files included in the zip file or on the CD-ROM, DVD, or USB flash drive shall contain all of the required test values as specified in Section 2.B.3.

These test values shall be provided in a directory labeled: KAT.

**2.C.3 Supporting Documentation** To facilitate the electronic distribution of submissions to all interested parties, copies of all written materials must also be submitted in electronic form in the PDF file format. Submitters are encouraged to use the thumbnail and bookmark features, to have a clickable table of contents (if applicable), and to include other links within the PDF as appropriate.

The electronic version of the supporting documentation shall be provided in a directory labeled: Supporting\_Documentation.

**2.C.4 General Requirements for Digital and Optical Media** For the portions of the submission that may be provided electronically, the information shall be provided using the ISO 9660 format. This media shall have the following structure:

- README
- Reference\_Implementation
- Optimized\_Implementation
- KAT
- Supporting\_Documentation

The “README” file shall be a plain text file and list all files that are included on the disc with a brief description of each.

All optical media presented to NIST must be free of viruses or other malicious code. The submitted media will be scanned for the presence of such code. If malicious code is found, NIST will notify the submitter and ask that a clean version of the optical media be

submitted.

## 2.D Intellectual Property Statements / Agreements / Disclosures

Each submitted algorithm, together with each submitted reference implementation and optimized implementation, must be made freely available for public review and evaluation purposes worldwide during the period of the **post**-quantum algorithm search and evaluation. The following signed statements will be required for a submission to be considered complete: 1) statement by the submitter, 2) statement by patent (and patent application) owner(s) (if applicable), and 3) statement by reference/optimized implementations' owner(s). Note that for the last two statements, separate statements must be completed if multiple individuals are involved.

Given the nature and use of cryptographic algorithms, NIST's PQC goals include identifying technically robust algorithms and facilitating their widespread adoption. NIST does not object in principle to algorithms or implementations which may require the use of a patent claim, where technical reasons justify this approach.

NIST has observed that royalty-free availability of cryptosystems and implementations has facilitated adoption of cryptographic standards in the past. As part of its evaluation of a PQC cryptosystem for standardization, NIST will consider the assurances made in the statements by the submitter(s) and any patent owner(s), with a strong preference for submissions as to which there are commitments to license, without compensation, under reasonable terms and conditions that are demonstrably free of unfair discrimination.

### 2.D.1 Statement by Each Submitter

I, \_\_\_\_\_ (print submitter's full name) \_\_\_\_\_, of \_\_\_\_\_ (print full postal address) \_\_\_\_\_, do hereby declare that the cryptosystem, reference implementation, or optimized implementations that I have submitted, known as \_\_\_\_\_ (print name of cryptosystem) \_\_\_\_\_, is my own original work, or if submitted jointly with others, is the original work of the joint submitters.

I further declare that (check one):

- I do not hold and do not intend to hold any patent or patent application with a claim which may cover the cryptosystem, reference implementation, or optimized implementations that I have submitted, known as \_\_\_\_\_ (print name of cryptosystem) \_\_\_\_\_; **OR** (check one or both of the following):
  - to the best of my knowledge, the practice of the cryptosystem, reference implementation, or optimized implementations that I have submitted, known as \_\_\_\_\_ (print name of cryptosystem) \_\_\_\_\_, may be covered by the following U.S. and/or foreign patents: \_\_\_\_\_ (describe and enumerate or state "none" if applicable) \_\_\_\_\_;
  - I do hereby declare that, to the best of my knowledge, the following pending U.S. and/or foreign patent applications may cover the practice of

*my submitted cryptosystem, reference implementation or optimized implementations: \_\_\_\_\_ (describe and enumerate or state "none" if applicable) \_\_\_\_\_.*

*I do hereby acknowledge and agree that my submitted cryptosystem will be provided to the public for review and will be evaluated by NIST, and that it might not be selected for standardization by NIST. I further acknowledge that I will not receive financial or other compensation from the U.S. Government for my submission. I certify that, to the best of my knowledge, I have fully disclosed all patents and patent applications which may cover my cryptosystem, reference implementation or optimized implementations. I also acknowledge and agree that the U.S. Government may, during the public review and the evaluation process, and, if my submitted cryptosystem is selected for standardization, during the lifetime of the standard, modify my submitted cryptosystem's specifications (e.g., to protect against a newly discovered vulnerability).*

*I acknowledge that NIST will announce any selected cryptosystem(s) and proceed to publish the draft standards for public comment*

*I do hereby agree to provide the statements required by Sections 2.D.2 and 2.D.3, below, for any patent or patent application identified to cover the practice of my cryptosystem, reference implementation or optimized implementations and the right to use such implementations for the purposes of the public review and evaluation process.*

*I acknowledge that, during the post-quantum algorithm evaluation process, NIST may remove my cryptosystem from consideration for standardization. If my cryptosystem (or the derived cryptosystem) is removed from consideration for standardization or withdrawn from consideration by all submitter(s) and owner(s), I understand that rights granted and assurances made under Sections 2.D.1, 2.D.2 and 2.D.3, including use rights of the reference and optimized implementations, may be withdrawn by the submitter(s) and owner(s), as appropriate.*

*Signed:  
Title:  
Date:  
Place:*

## **2.D.2 Statement by Patent (and Patent Application) Owner(s)**

If there are any patents (or patent applications) identified by the submitter, including those held by the submitter, the following statement must be signed by each and every owner, or each owner's authorized representative, of each patent and patent application identified.

*I, \_\_\_\_\_ (print full name) \_\_\_\_\_, of \_\_\_\_\_ (print full postal address) \_\_\_\_\_, am the owner or authorized representative of the owner (print full name, if different than the signer) of the following patent(s) and/or patent application(s): \_\_\_\_\_ (enumerate) \_\_\_\_\_, and do hereby commit and agree to grant to any interested party on a*

worldwide basis, if the cryptosystem known as \_\_\_\_\_ (print name of cryptosystem) \_\_\_\_\_ is selected for standardization, in consideration of its evaluation and selection by NIST, a non-exclusive license for the purpose of implementing the standard (check one):

- without compensation and under reasonable terms and conditions that are demonstrably free of any unfair discrimination, **OR**
- under reasonable terms and conditions that are demonstrably free of any unfair discrimination.

I further do hereby commit and agree to license such party on the same basis with respect to any other patent application or patent hereafter granted to me, or owned or controlled by me, that is or may be necessary for the purpose of implementing the standard.

I further do hereby commit and agree that I will include, in any documents transferring ownership of each patent and patent application, provisions to ensure that the commitments and assurances made by me are binding on the transferee and any future transferee.

I further do hereby commit and agree that these commitments and assurances are intended by me to be binding on successors-in-interest of each patent and patent application, regardless of whether such provisions are included in the relevant transfer documents.

I further do hereby grant to the U.S. Government, during the public review and the evaluation process, and during the lifetime of the standard, a nonexclusive, nontransferrable, irrevocable, paid-up worldwide license solely for the purpose of modifying my submitted cryptosystem's specifications (e.g., to protect against a newly discovered vulnerability) for incorporation into the standard.

Signed:  
Title:  
Date:  
Place:

### **2.D.3 Statement by Reference/Optimized Implementations' Owner(s)**

The following must also be included:

I, \_\_\_\_\_ (print full name) \_\_\_\_\_, (print full postal address) \_\_\_\_\_, am the owner or authorized representative of the owner (print full name, if different than the signer) of the submitted reference implementation and optimized implementations and hereby grant the U.S. Government and any interested party the right to reproduce, prepare derivative works based upon, distribute copies of, and display such implementations for the purposes of the post-quantum algorithm public review and evaluation process, and implementation if the corresponding cryptosystem is selected for standardization and as

*a standard, notwithstanding that the implementations may be copyrighted or copyrightable.*

*Signed:*

*Title:*

*Date:*

*Place:*

## **2.E General Submission Requirements**

NIST welcomes both domestic and international submissions; however, in order to facilitate analysis and evaluation, it is required that the submission packages be in English. This requirement includes the cover sheet, algorithm specification and supporting documentation, source code, and intellectual property information. Any required information that is not submitted in English shall render the submission package “incomplete.” Optional supporting materials (e.g., journal articles) in another language may be submitted.

Classified and/or proprietary submissions will not be accepted.

## **2.F Technical Contacts and Additional Information**

For technical inquiries, send e-mail to [pqc-comments@nist.gov](mailto:pqc-comments@nist.gov), or contact Lily Chen, National Institute of Standards and Technology, 100 Bureau Drive—Stop 8930, Gaithersburg, MD 20899–8930; telephone: +1 301–975–6974 or via fax at +1 301–975–8670, e-mail: [lily.chen@nist.gov](mailto:lily.chen@nist.gov).

Answers to germane questions will be posted at <http://www.nist.gov/pqcrypto>. Questions and answers that are not pertinent to this announcement may not be posted. NIST will endeavor to answer all questions in a timely manner.

## **3. Proposed Minimum Acceptability Requirements**

Those submission packages that are deemed by NIST to be “complete” will be evaluated for the inclusion of a “proper” post-quantum public-key cryptosystem. To be considered as a “proper” post-quantum public-key cryptosystem (and continue further in the standardization process), the scheme shall meet the following minimum acceptability requirements:

1. The algorithms shall be publicly disclosed and made available for public review and the evaluation process, and for standardization if selected, freely (i.e., shall be dedicated to the public), or shall be made available in accordance with Sections 2.D.1, 2.D.2 and 2.D.3, as applicable.
2. The algorithms shall not incorporate major components that are believed to be insecure against quantum computers. (For example, hybrid schemes that include encryption or signatures based on factoring or discrete logs will not be considered for standardization by NIST in this context.)



3. The algorithms shall provide at least one of the following functionalities: public-key encryption, key exchange, or digital signature:
  - a. Public-key encryption schemes shall include algorithms for key generation, encryption, and decryption. The key generation algorithm shall generate public and private keys, such that messages or symmetric keys encrypted with the public key are recoverable with high probability by decryption with the corresponding private key. If decryption failure is a possibility, it shall occur at a rate consistent with claims made by the submitter. At a minimum, the scheme shall support the encryption and decryption of messages that contain symmetric keys of length at least 256 bits.
  - b. KEM schemes shall include algorithms for key generation, encapsulation and decapsulation. The key generation algorithm shall generate public and private key pairs, such that encapsulation with the public key and decapsulation with the private key produce the same shared secret, when the encapsulated ciphertext is given as an input to the decapsulate function. If decapsulation failure is a possibility, it shall occur at a rate consistent with claims made by the submitter. At a minimum, the KEM functionality shall support the establishment of shared keys of length at least 256 bits.
  - b. ~~Key exchange schemes shall include algorithms for generating initiator and responder key exchange messages, as well as algorithms for both initiator and responder to recover a shared secret. Initiators and responders conforming to the specified schemes shall recover the same secret with high probability. If failed key establishment is a possibility, it shall occur at a rate consistent with claims made by the submitter. At a minimum, the key exchange functionality shall support the establishment of shared keys of length at least 256 bits.~~
  - c. Digital-signature schemes shall include algorithms for key generation, signature, and verification. The key generation algorithm shall generate public and private keys, such that a message signed with the private key will be successfully verified with the corresponding public key. The scheme shall be capable of supporting a message size up to  $2^{63}$  bits.
4. The submission package shall provide concrete values for any parameters and settings required to achieve the claimed security properties (to the best of the submitter's knowledge.)

~~The submission package shall provide concrete values for any parameters and settings required to meet or exceed (to the best of the submitter's knowledge) the relevant security targets in Section 4.A.4, for the appropriate security models in Sections 4.A.2 and 4.A.3.~~

A submission package that is complete (as defined in Section 2) and meets the minimum acceptability requirements (as defined immediately above) will be deemed to be a “complete and proper” submission. A submission that NIST deems otherwise at the close of the submission period will receive no further consideration. Submissions that are “complete and proper” will be posted at <http://www.nist.gov/pqcrypto> for public review.

#### 4. Proposed Evaluation Criteria

NIST will form an internal selection panel composed of NIST employees to analyze the submitted algorithms; the evaluation process will be discussed in Section 5. All of NIST's analysis results will be made publicly available.

Although NIST will be performing its own analyses of the submitted algorithms, NIST strongly encourages public evaluation and publication of the results. NIST will take into account its own analysis, as well as the public comments that are received in response to the posting of the "complete and proper" submissions, to make its decisions.

To avoid unnecessary duplication of effort, and to streamline the evaluation process, NIST encourages researchers who are developing similar cryptosystems to combine their efforts and produce a single submission package.

#### 4.A Security

The security provided by a cryptographic scheme is the most important factor in the evaluation. Schemes will be judged on the following factors:

**4.A.1 Applications of Public-Key Cryptography** NIST intends to standardize ~~post-quantum-resistant~~ alternatives to its existing standards for digital signatures (FIPS 186) and key establishment (SP 800-56A, SP 800-56B). These standards are used in a wide variety of Internet protocols, such as TLS, SSH, IKE, IPsec, and DNSSEC. Schemes will be evaluated by the security they provide in these applications, and in additional applications that may be brought up by NIST or the public during the evaluation process. Claimed applications will be evaluated for their practical importance if this evaluation is necessary for deciding which algorithms to standardize.

#### 4.A.2 Security Model for ~~General Purpose Encryption/Key Establishment~~

~~One particularly important application of public-key cryptography is to securely establish a key to be used for symmetric encryption. In previous publications [SP800-57], NIST has distinguished between two methods of achieving this functionality. The first method uses public-key encryption algorithms (such as RSA), known in this context as key transport algorithms, while the second uses KEMs (such as Diffie-Hellman), known in this context as key agreement or key exchange. NIST expects submitters of encryption and KEM schemes to be aware of this application. NIST intends to standardize one or more schemes that enable "semantically secure" encryption or key encapsulation with respect to adaptive chosen ciphertext attack, for general use. This property is generally denoted IND-CCA2 security in academic literature. One particularly important application of public-key cryptography is key transport (i.e., public-key encryption of a symmetric key). NIST has previously specified how to use both public-key encryption algorithms (such as RSA), and key agreement algorithms (such as Diffie-Hellman) to achieve this functionality. NIST expects submitters of encryption and key agreement algorithms to do the same. NIST intends to standardize one or more schemes that enable "semantically secure encryption" with respect to adaptive chosen ciphertext attack. (This property is generally denoted IND-CCA2 security in academic literature.)~~

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The above security model should be taken as a statement of what NIST will consider to be a relevant attack. Submitted [KEM and encryption schemes](#) ~~for encryption and key exchange~~ will be evaluated based on how well they appear to provide this property, when used as specified by the submitter. Submitters are not required to provide a proof of security, although such proofs will be considered if they are available.

For the purpose of estimating security strengths, it may be assumed that the attacker has access to the decryptions of no more than  $2^{64}$  chosen ciphertexts; however, attacks involving more ciphertexts may also be considered. Additionally, it should be noted that NIST is primarily concerned with attacks that use classical (rather than quantum) queries to the decryption oracle or other private-key functionality.

[4.A.3 Security Model for Ephemeral-Only Encryption/Key-Establishment While chosen ciphertext security is necessary for many existing applications \(for example, nominally ephemeral key exchange protocols that allow key caching\), it is possible to implement a purely ephemeral key exchange protocol in such a way that only passive security is required from the encryption or KEM primitive.](#)

[For these applications, NIST will consider standardizing an encryption or KEM scheme which provides semantic security with respect to chosen plaintext attack. This property is generally denoted \*IND-CPA security\* in academic literature.](#)

[The above security model should be taken as a statement of what NIST will consider to be a relevant attack. Submitted KEM and encryption schemes will be evaluated based on how well they appear to provide this property, when used as specified by the submitter. Submitters are not required to provide a proof of security, although such proofs will be considered if they are available. Any security failures/vulnerabilities that result from re-using a key should be fully explained.](#)

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I prefer "vulnerabilities" for violations of security as opposed to correctness.

**4.A.4 Security Model for Digital Signatures** NIST intends to standardize one or more schemes that enable existentially unforgeable digital signatures with respect to an adaptive chosen message attack. (This property is generally denoted *EUF-CMA security* in academic literature.)

The above security model should be taken as a statement of what NIST will consider to be a relevant attack. Submitted algorithms for digital signatures will be evaluated based on how well they appear to provide this property when used as specified by the submitter. Submitters are not required to provide a proof of security, although such proofs will be considered if they are available.

For the purpose of estimating security strengths, it may be assumed that the attacker has access to signatures for no more than  $2^{64}$  chosen messages; however, attacks involving more messages may also be considered. Additionally, it should be noted that NIST is primarily concerned with attacks that use classical (rather than quantum) queries to the signing oracle.

4.A.5 Security Strength Categories NIST will classify submitted parameter sets based on the computational cost of attacking them under a variety of plausible scenarios regarding future progress in classical and quantum computing. The goals of this classification are:

- 1) To facilitate meaningful performance comparisons between the submitted algorithms, by ensuring, insofar as possible, that the parameter sets being compared provide comparable security.
- 2) To allow NIST to make consistent and sensible future decisions regarding when to transition to longer keys.
- 3) To better understand the security/performance tradeoffs involved in a given design approach.

In accordance with the second goal above, NIST will base its classification on the range of security strengths offered by the existing NIST standards in symmetric cryptography, which NIST expects to offer significant resistance to quantum cryptanalysis. In particular, NIST will classify the parameter sets being considered for standardization into the following categories:

- 1) Violating the relevant security model requires computational resources comparable to or greater than required for key search on a block cipher with a 128-bit key (e.g. AES128)
- 2) Violating the relevant security model requires computational resources comparable to or greater than required for collision search on a 256-bit hash function (e.g. SHA256/ SHA3-256)
- 3) Violating the relevant security model requires computational resources comparable to or greater than key search on a block cipher with a 192-bit key (e.g. AES192)
- 4) Violating the relevant security model requires computational resources comparable to or greater than required for collision search on a 384-bit hash function (e.g. SHA384/ SHA3-384)
- 5) Violating the relevant security model requires computational resources comparable to or greater than required for key search on a block cipher with a 256-bit key. (e.g. AES 256)

In categorizing submitted parameter sets, NIST will take into account a variety of measures of computational work (e.g. classical security, quantum circuit size at limited depth, combined measures based on the expected cost differential between classical and quantum gates etc.). Which measure is most relevant to practical security will depend on future developments in both classical and quantum computing technology. If plausibly relevant measures yield different categorizations of a parameter set, NIST will generally categorize the parameter set as meeting the lower category. Note that, barring some truly surprising technological development during the standardization process, NIST will assume that the 5 security strengths are correctly ordered in terms of practical security. (E.g., NIST will assume that a brute-force collision attack on SHA256 will be

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technologically feasible before a brute-force key search attack on AES192.) Note also that security strengths 1, 3, and 5 are defined in such a way that they are likely to be met by any scheme that:

- Provides classical security strength of 128, 192, and 256 bits, respectively, AND
- Is not subject to quantum attacks, other than classical attacks sped up by generic techniques (Grover’s algorithm, quantum walks, amplitude amplification etc.)

As NIST will be relying heavily on analysis from the cryptographic community, including the submitters, in its evaluations, NIST asks submitters to provide a preliminary classification, according to the above categories, for all parameter sets that they intend to be considered for standardization. All submitters are advised to be somewhat conservative in their preliminary classifications, but submitters of algorithms where the complexity of the best known attack has recently decreased significantly, or is otherwise poorly understood, should be especially conservative.

NIST will not require submitters to provide distinct parameter sets for all five security-strength categories. Submitted parameter sets meeting the requirements of a higher category will be automatically considered to meet the requirements of all lower categories. NIST recommends that submitters provide at least one parameter set that can be provisionally classified as having security strength 4 or 5, and as many additional parameter sets as they feel are appropriate to take advantage of any available security/performance tradeoffs.

**4.A.6 Measures of Computational Work** While NIST will continue throughout the evaluation process to accept input from the cryptographic community regarding which measures of computational work will be most predictive of the security lifetime of submitted algorithms and parameter sets, NIST can offer a number of security metrics that it currently believes are likely to be relevant. These include classical security, quantum circuit size at limited depth, and hybrid measures that assign a lower cost to classical components and/or small quantum components that do not need to share entanglement with other parts of the computation.

For algorithms not subject to dramatic quantum attacks, such as those involving Shor’s algorithm, NIST believes that classical measures of security will continue to be highly relevant. Currently envisioned quantum computing technologies would be orders of magnitude slower and more energy intensive than today’s classical computing technology, when performing the same sorts of operations. When these considerations are combined with the poor parallelization of Grover’s algorithm, it becomes quite likely that variants of Grover’s algorithm will provide no advantage to an adversary wishing to perform a cryptanalytic attack that can be completed in a matter of years, or even decades. As most quantum attacks on proposed postquantum cryptosystems have involved some variant of Grover’s algorithm, it may be the case that the best attack in practice will simply be the classical attack.

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Nonetheless, NIST does consider the sort of dramatic improvements in quantum computing technology, that will make Grover's algorithm a relevant security threat, a real possibility. Even in this case, however, adversaries will only be able to perform computations of limited depth, if they wish to complete an attack in a reasonable timespan (e.g. 10 years or less). Circuit size at limited depth could also be used to evaluate classical algorithms. However, most cryptanalytically relevant classical algorithms have similar time-space tradeoffs in the regime relevant to security. NIST would therefore expect this measure to give similar results to standard measures of classical security.

Plausible limitations on depth range from  $2^{40}$  logical gates (the approximate number of gates that presently envisioned quantum computing architectures like quDOS are expected to serially perform in a year) through  $2^{64}$  logical gates (the approximate number of gates that current classical computing architectures can perform serially in a decade), to  $2^{96}$  logical gates (the approximate number of gates that atomic scale qubits with speed of light propagation times could perform in a millennium). It should be noted that, if one assumes a depth limitation on the extreme high end of this range and a small gap between the cost of classical and quantum gates, this measure would suggest that our security strengths are incorrectly ordered (with security strength 2 being more secure than security strength 3 and security strength 4 being more secure than security strength 5). NIST would be surprised if such a measure became practically relevant before the lowest 3 security strengths have become obsolete, but it remains somewhat possible that security strengths 4 and 5 may be incorrectly ordered. For the purpose of the evaluation process, NIST will, however, ignore this possibility: standard constructions for converting between KEM and key transport functionality, for example, involve block ciphers, and NIST has not approved a block cipher offering more security than AES 256. In any event, NIST expects both security strengths 4 and 5 to be sufficiently secure for the foreseeable future.

Finally, NIST intends to consider other more detailed models of computation, which take into account other factors that may affect the efficiency of a real world implementation of a quantum algorithm. These include, the possibility of performing large portions of the computation classically, the possibility of dividing the computation into smaller quantum computations that do not need to share quantum entanglement, and the possibility of implementing the computation in an architecture, such as adiabatic quantum computation, which is intermediate in ease of implementation between classical and quantum computation.

For reference, at the present time, NIST would give the following estimates for the classical and quantum gate counts for the optimal key recovery and collision attacks on AES and SHA3, respectively, where circuit depth is limited to MAXDEPTH. (Quantum circuit sizes are based on <https://arxiv.org/abs/1512.04965> which was also published at [http://link.springer.com/chapter/10.1007%2F978-3-319-29360-8\\_3](http://link.springer.com/chapter/10.1007%2F978-3-319-29360-8_3).)

AES128:  $2^{170}$ /MAXDEPTH quantum gates or  $2^{143}$  classical gates.  
SHA3-256:  $2^{146}$  classical gates.

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AES192:  $2^{233}$ /MAXDEPTH quantum gates or  $2^{207}$  classical gates.

SHA3-384:  $2^{210}$  classical gates.

AES256:  $2^{298}$ /MAXDEPTH quantum gates or  $2^{272}$  classical gates.

SHA3512:  $2^{274}$  classical gates. Submitters are asked to provide parameter sets that meet or exceed each of five target security strengths:

128 bits classical security / 64 bits quantum security

128 bits classical security / 80 bits quantum security

192 bits classical security / 96 bits quantum security

192 bits classical security / 128 bits quantum security

256 bits classical security / 128 bits quantum security

In specifying these security strengths, the intent is that parameter sets meeting security strengths 1, 3, and 5 will remain secure as long as brute force attacks against AES-128, AES-192, and AES-256, respectively, remain infeasible. Likewise, parameter sets meeting security strengths 2 and 4 should remain secure roughly as long as brute force collision attacks against SHA-256/SHA3-256 and SHA-384/SHA3-384, respectively, remain infeasible.

NIST recognizes that quantum cryptanalysis is a subject of ongoing research. There are significant uncertainties about the theoretical capabilities of quantum algorithms, and the practical feasibility of building quantum computers on a scale relevant for cryptanalysis. Two particular issues are of concern to NIST:

Measuring the complexity of quantum cryptanalytic attacks; and

Determining whether a post-quantum cryptographic scheme achieves one of the target security strengths described above.

At this point, NIST is providing some preliminary guidance to address these issues. NIST anticipates that further discussion will be needed within the cryptographic community in order to achieve consensus regarding these questions.

First, when describing quantum cryptanalytic attacks, NIST encourages researchers to report both the time and space complexity of a quantum algorithm, and to consider ways in which an algorithm may be parallelized, to achieve a range of possible tradeoffs between space and time complexity.

NIST is concerned with the most practical attack on a cryptosystem, which may not be the one requiring the smallest total number of operations. In particular, an attack requiring a larger number of operations may be more practical than one that requires fewer operations, if the former is more amenable to speedup via parallel execution (i.e., reducing its time complexity by performing more computations in parallel).

One of the simplest examples of this phenomenon involves hash functions: A quantum preimage attack on a  $2s$ -bit hash function, using Grover's algorithm, has roughly the same complexity as a classical search for collisions on the same  $2s$ -bit hash function (ignoring costs associated with reversibility, fault tolerance, etc.). However, Grover's algorithm parallelizes significantly more poorly than classical collision search. As a

result, in a realistic scenario where the attacker performs many operations in parallel, a classical search for collisions on a  $2s$ -bit hash has a significantly lower time complexity than quantum preimage search on the same hash function.

Regarding the target security strengths, NIST's goal is that post-quantum cryptographic schemes that claim to have  $s$  bits of quantum security must be at least as secure as a block cipher with a  $2s$ -bit key. Ideally, such schemes should be secure against quantum attacks that use any degree of parallelism, but NIST recognizes that extremely serial or extremely parallel attacks (e.g., those that have a time depth or space complexity exceeding  $2^{100}$ ) may be of minimal practical importance.

Some care is needed to precisely define the meaning of these security strengths. Intuitively,  $k$  bits of classical security means that the best cryptanalytic attack requires  $2^k$  classical computing resources, and  $k$  bits of quantum security means that the best cryptanalytic attack requires  $2^k$  quantum computing resources. To make this statement precise, however, one must choose appropriate units for measuring computational complexity, memory requirements etc. To resolve this ambiguity, NIST proposes to *define* the units of computational work to be such that AES-128 has 128 bits of classical security and 64 bits of quantum security (under the assumption that there are no attacks on AES that require significantly less work than a brute-force search). Under this assumption, the best quantum attack is given by Grover's algorithm, and the tradeoffs between time and space complexity are well known.

(It is worth noting that another possible approach would be to define security with respect to a hash function such as SHA-256 / SHA3-256, rather than a block cipher. This definition would not be equivalent to the definition based on AES-128, as it would involve collision finding rather than unstructured search. This would imply different tradeoffs between time and space complexity, which may be of interest. However, this definition has the disadvantage of being less familiar to cryptographers who are unfamiliar with quantum algorithms.)

In addition to time complexity, NIST will consider other factors that affect the feasibility of an attack, such as how easily the attack can be parallelized, and whether the attack can be implemented using special-purpose hardware (such as hybrid quantum-classical architectures, quantum annealers, graphics processing units, neuromorphic architectures, and others).

Finally, it appears that quantum computations will be significantly more expensive to perform than classical computations using current and near-future technologies, due to the need for quantum error correction and distinctive hardware requirements, such as extreme cooling. However, the development of quantum computing hardware is difficult to predict. For the purpose of developing post-quantum cryptosystems, it may be prudent to plan for the extreme scenario where quantum computers will be relatively cheap and ubiquitous. NIST will therefore take quantum attacks seriously, even if they require the full power of a general-purpose quantum computer.



**4.A.7 Additional Security Properties** While the previously listed security definitions cover many of the attack scenarios that will be used in the evaluation of the submitted algorithms, there are several other properties that would be desirable:

One such property is perfect forward secrecy<sup>2</sup>. While this property can be obtained through the use of standard encryption and signature functionalities, the cost of doing so may be prohibitive in some cases. In particular, public-key encryption schemes with a slow key generation algorithm, such as RSA, are typically considered unsuitable for perfect forward secrecy. This is a case where there is significant interaction between the cost, and the practical security, of an algorithm.

Another case where security and performance interact is resistance to side-channel attacks. Schemes that can be made resistant to side-channel attack at minimal cost are more desirable than those whose performance is severely hampered by any attempt to resist side-channel attacks. We further note that optimized implementations that address side-channel attacks (e.g., constant-time implementations) are more meaningful than those which do not.

A third desirable property is resistance to multi-key attacks. Ideally an attacker should not gain an advantage by attacking multiple keys at once, whether the attacker's goal is to compromise a single key pair, or to compromise a large number of keys.

A final desirable, although ill-defined, property is resistance to misuse. Schemes should ideally not fail catastrophically due to isolated coding errors, random number generator malfunctions, nonce reuse, keypair reuse (for ephemeral-only encryption/key establishment) etc.

Commented [PR(12)]: Given we are now allowing IND-CPA KEM/PKE, I have added this example.

**4.A.8 Other Consideration Factors** As public-key cryptography tends to contain subtle mathematical structure, it is very important that the mathematical structure be well understood in order to have confidence in the security of a cryptosystem. To assess this, NIST will consider a variety of factors. All other things being equal, simple schemes tend to be better understood than complex ones. Likewise, schemes whose design principles can be related to an established body of cryptographic-relevant research tend to be better understood than schemes that are completely new, or schemes that were designed by repeatedly patching older schemes that were shown vulnerable to cryptanalysis.

NIST will also consider the clarity of the documentation of the scheme and the quality of the analysis provided by the submitter. Clear and thorough analysis will help to develop the quality and maturity of analysis by the wider community. NIST will also consider any security arguments or proofs provided by the submitter. While security proofs are generally based on unproven assumptions, they can often rule out common classes of attacks or relate the security of a new scheme to an older and better studied computational problem.

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<sup>2</sup> The term perfect forward secrecy is commonly used to denote a feature of key agreement protocols which gives assurances that past session keys will not be compromised even if the private key of the server is compromised.

In addition to NIST's own expectations for the scheme's long-term security, NIST will also consider the judgment and opinions of the broader cryptographic community.

#### 4.B Cost

As the cost of a public-key cryptosystem can be measured on many different dimensions, NIST will continually seek public input regarding which performance metrics and which applications are most important. If there are important applications that require radically different performance tradeoffs, NIST may need to standardize more than one algorithm to meet these diverse needs.

**4.B.1 Public Key, Ciphertext, and Signature Size** Schemes will be evaluated based on the sizes of the public keys, ciphertexts, and signatures that they produce. All of these may be important consideration factors for bandwidth-constrained applications or in Internet protocols that have a limited packet size. The importance of public-key size may vary depending on the application; if applications can cache public keys, or otherwise avoid transmitting them frequently, the size of the public key may be of lesser importance. In contrast, applications that seek to obtain perfect forward secrecy by transmitting a new public key at the beginning of every session are likely to benefit greatly from algorithms that use relatively small public keys.

**4.B.2 Computational Efficiency of Public and Private Key Operations** Schemes will also be evaluated based on the computational efficiency of the public key (encryption, [encapsulation](#), and signature verification) and private key (decryption, [decapsulation](#), and signing) operations. The computational cost of these operations will be evaluated both in hardware and software. The computational cost of both public and private key operations is likely to be important for almost all operations, but some applications may be more sensitive to one or the other. For example, signing or decryption operations may be done by a computationally constrained device like a smartcard; or alternatively, a server dealing with a high volume of traffic may need to spend a significant fraction of its computational resources verifying client signatures.

**4.B.3 Computational Efficiency of Key Generation** Schemes will also be evaluated based on the computational efficiency of their key generation operations, where applicable. As noted in Section 4.A.7, the most common scenario where key generation time is important is when a public-key encryption [algorithm or a KEM](#) is used to provide perfect forward secrecy. Nonetheless, it is possible that key generation times may also be important for digital signature schemes in some applications.

**4.B.4 Decryption Failures** Some public-key encryption algorithms [and KEMs](#), even when correctly implemented, will occasionally produce ciphertexts that cannot be decrypted/[decapsulated](#). For most applications, it is important that such decryption failures be rare or absent. [For algorithms with decryption/decapsulation failures, submitters must provide the failure rate, as well as an analysis of the impact on security that these failures could cause.](#) While applications can always obtain an acceptably low

**Commented [MD(13):** We agree that we should add another paragraph/item which deals with the cost considerations of key exchange/establishment. For example, could mention number of rounds of communication, number of static or ephemeral keys required, whether or not the protocol supports (or requires) synchronous or asynchronous communication.

**Commented [RP14R13]:** Since we are explicitly defining the number of rounds and the number of keys by using the KEM framework for the key exchange option, I don't think we need to mention anything here. However, this comment is partially accepted in 4.B.4 and 4.C.1

decryption failure rate by encrypting the same [plaintext](#) multiple times, [and interactive protocols can simply restart when key establishment fails](#), ~~this~~ [these](#) types of solutions [have their](#) ~~has its~~ own performance costs.

#### 4.C Algorithm and Implementation Characteristics

**4.C.1 Flexibility** Assuming good overall security and performance, schemes with greater flexibility will meet the needs of more users than less flexible schemes, and therefore, are preferable.

Some examples of “flexibility” may include (but are not limited to) the following:

- a. The scheme can be modified to provide additional functionalities that extend beyond the minimum requirements of public-key encryption, [KEM](#), or digital signatures (e.g., [optimized asynchronous](#) or implicitly authenticated key exchange, etc.).
- b. It is straightforward to customize the scheme’s parameters to meet a range of security targets and performance goals.
- c. The algorithms can be implemented securely and efficiently on a wide variety of platforms, including constrained environments, such as smart cards.
- d. Implementations of the algorithms can be parallelized to achieve higher performance.
- e. [The scheme can be incorporated into existing protocols and applications, requiring as few changes as possible.](#)

**4.C.2 Simplicity** The submitted scheme will be judged according to its relative design simplicity.

### 5. Proposed Evaluation Process

NIST will form an internal selection panel composed of NIST employees for the technical evaluations of the submitted algorithms. This panel will analyze the submitted algorithms and review public comments that are received in response to the posting of the “complete and proper” submissions. The panel will also take into account all presentations, discussions and technical papers presented at the PQC standardization conferences, as well as other pertinent papers and presentations made at other cryptographic research conferences and workshops. NIST will issue a report after each PQC standardization conference. Final selections of cryptosystems will be made by NIST and the technical rationale for these decisions will be documented in a final report. The following is an overview of the envisioned submission review process.

#### 5.A Overview

Following the close of the call for submission packages, NIST will review the received packages to determine which are “complete and proper,” as described in Sections 2 and 3 of this notice. NIST will post all “complete and proper” submissions at

<http://www.nist.gov/pqcrypto> for public review. To help inform the public, a PQC standardization conference will be held at the start of the public comment process to allow submitters to publicly explain and answer questions regarding their submissions.

The initial phase of evaluation will consist of approximately twelve to eighteen months of public review of the submitted algorithms. During this initial review period, NIST intends to evaluate the submitted algorithms as outlined in Section 5.B. NIST will review the public evaluations of the submitted algorithms' cryptographic strengths and weaknesses, and will use these to narrow the candidate pool for more careful study and analysis. The purpose of this selection process is to identify candidates that are suitable for standardization in the near future. Algorithms that are not included in the narrowed pool may still be considered for standardization at a later date, unless they are explicitly removed from consideration by NIST.

Because of limited resources, and also to avoid moving evaluation targets (i.e., modifying the submitted algorithms undergoing public review), NIST will NOT accept modifications to the submitted algorithms during this initial phase of evaluation.

For informational and planning purposes, near the end of the initial public evaluation process, NIST intends to hold another PQC standardization conference. Its purpose will be to publicly discuss the submitted algorithms, and to provide NIST with information for narrowing the field of algorithms for continued evaluation.

NIST plans to narrow the field of algorithms for further study, based upon its own analysis, public comments, and all other available information. It is envisioned that this narrowing will be done primarily on security, efficiency, and intellectual property considerations. NIST will issue a report describing its findings. Submitters of sufficiently similar algorithms may be asked to merge submissions for the next phase.

Before the start of a second evaluation period, the submitters of the algorithms will have the option of providing updated optimized implementations for use during the next phase of the evaluation. During the course of the initial evaluations, it is conceivable that some small deficiencies may be identified in even some of the most promising submissions. Therefore, for the second round of evaluations, small modifications to the submitted algorithms will be permitted for either security or efficiency purposes. Submitters may submit minor changes (no substantial redesigns), along with a supporting justification that must be received by NIST prior to the beginning of the second evaluation period. (Submitters will be notified by NIST of the exact deadline.) NIST will determine whether the proposed modification would significantly affect the design of the algorithm, requiring a major re-evaluation; if such is the case, the modification will not be accepted. If modifications are submitted, new reference and optimized implementations and written descriptions must also be provided by the announced deadline. This will allow a thorough public review of the modified algorithms during the entire course of the second evaluation phase.

**Note:** All proposed changes must be ~~proposed~~ conveyed by the submitter; no proposed changes (to the algorithm or implementations) will be accepted from a third party.

The second round of evaluation will consist of approximately twelve to eighteen months of public review, with a focus on a narrowed pool of candidate algorithms. During the public review, NIST will similarly evaluate these algorithms as outlined in the next section. After the end of the public review period, NIST intends to hold another PQC standardization conference. (The exact date is to be scheduled.)

Following the third PQC standardization conference, NIST will prepare a summary report, which may select algorithm(s) for possible standardization, and/or may determine that a third phase of evaluation is needed. This third evaluation process would be structured similarly to the previous two evaluation periods. Any selected algorithm(s) for standardization will be incorporated into draft standards, which will be made available for public comment.

When evaluating algorithms, NIST will make every effort to obtain public input and will encourage the review of the submitted algorithms by outside organizations. NIST encourages the reviewers to demonstrate their findings and attacks both on the versions with parameters that achieve full security levels, as well as with practical attacks on the provided parameter sets with lower security levels. The final decision as to which (if any) algorithm(s) will be selected for standardization is the responsibility of NIST.

It should be noted that this schedule for the evaluation process is somewhat tentative, depending upon the type, quantity, and quality of the submissions. Specific conference dates and public comment periods will be announced at appropriate times in the future. NIST estimates that some algorithms could be selected for standardization after three to five years. However, due to developments in the field, this could change.

## **5.B Technical Evaluation**

NIST will invite public comments on all “complete and proper” submissions. The analysis done by NIST during the initial phase of evaluation is intended, at a minimum, to include:

- i. *Correctness check:* The KAT values included with the submission will be used to test the correctness of the reference and optimized implementations, once they are compiled. (It is more likely that NIST will perform this check of the reference code—and possibly the optimized code as well—even before accepting the submission package as “complete and proper.”)
- ii. *Efficiency testing:* Using the submitted optimized implementations, NIST intends to perform various computational efficiency tests. This could include, for example, the time required for key generation, encryption, decryption, digital signing, signature verification, or key establishment, as well as the size of keys, ciphertext, and signatures.

iii. *Other testing*: Other features of the submitted algorithms may be examined by NIST.

### **Platform and Compilers**

The above tests will initially be performed by NIST on the *NIST PQC Reference Platform*, an Intel x64 running Windows or Linux and supporting the GCC compiler.

At a minimum, NIST intends to perform an efficiency analysis on the reference platform; however, NIST invites the public to conduct similar tests and compare results on additional platforms (e.g., 8-bit processors, digital signal processors, dedicated CMOS, etc.). NIST may also perform efficiency testing using additional platforms.

NIST welcomes comments regarding the efficiency of the submitted algorithms when implemented in hardware. During the second evaluation period, NIST may request specifications of some of the algorithms using a hardware description language, to compare the estimated hardware efficiency of the submitted algorithms.

Note: If the submitter chooses to submit updated optimized implementations prior to the beginning of the second round of evaluation, then some of the tests performed may be performed again using the new optimized implementations. This will be done to obtain updated measurements.

Note: Any changes to the NIST PQC Reference Platform will be noted on <http://www.nist.gov/pqcrypto>.

### **5.C Initial Planning for the First PQC Standardization Conference**

An open public conference will be held shortly after the end of the submission period, at which the submitters of each “complete and proper” submission package will be invited to publicly discuss and explain their submitted algorithm. The documentation for these algorithms will be made available at the conference. Details of the conference will be posted at <http://www.nist.gov/pqcrypto>.

### **Appreciation**

NIST extends its appreciation to all submitters and those providing public comments during the ~~post-quantum-resistant~~ algorithm evaluation process.

Dated: xxx