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Composite ML-KEM for use in X.509 Public Key Infrastructure
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Abstract

This document defines combinations of US NIST ML-KEM in hybrid with traditional algorithms RSA-OAEP, ECDH, X25519, and X448. These combinations are tailored to meet security best practices and regulatory guidelines. Composite ML-KEM is applicable in any application that uses X.509 or PKIX data structures that accept ML-KEM, but where the operator wants extra protection against breaks or catastrophic bugs in ML-KEM.

About This Document

This note is to be removed before publishing as an RFC.

The latest revision of this draft can be found at https://lamps-wg.github.io/draft-composite-kem/draft-ietf-lamps-pq-composite-kem.html. Status information for this document may be found at https://datatracker.ietf.org/doc/draft-ietf-lamps-pq-composite-kem/.

Discussion of this document takes place on the LAMPS Working Group mailing list (mailto:spams@ietf.org), which is archived at https://datatracker.ietf.org/wg/lamps/about/. Subscribe at https://www.ietf.org/mailman/listinfo/spams/.

Source for this draft and an issue tracker can be found at https://github.com/lamps-wg/draft-composite-kem.

Status of This Memo

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1. Introduction

The advent of quantum computing poses a significant threat to current cryptographic systems because traditional cryptographic key establishment algorithms such as RSA-OAEP, Diffie-Hellman and its elliptic curve variants will become vulnerable to quantum attacks. Unlike previous migrations between cryptographic algorithms, this migration gives us the foresight that traditional cryptographic algorithms will be broken in the future, but will remain strong in the interim, the only uncertainty is around the timing. But there are also some novel challenges. For instance, the aggressive migration timelines may require deploying PQC algorithms before their implementations have been fully hardened or certified, and dual-algorithm data protection may be desirable over a longer time period to hedge against security vulnerabilities and other implementation flaws in the new implementations.

Cautious implementers may opt to combine cryptographic algorithms in such a way that an attacker would need to break all of them simultaneously to compromise the protected data. These mechanisms are referred to as "Post-Quantum / Traditional (PQ/T) Hybrids" [RFC9794].

This specification defines a specific instantiation of the PQ/T Hybrid paradigm called "composite" where multiple cryptographic algorithms are combined to form a single key encapsulation mechanism (KEM). The composite KEM presents a single public key and ciphertext such that it can be treated as a single atomic algorithm at the protocol level. This provides a property referred to as "protocol backwards compatibility" since it can be applied to protocols that are not explicitly hybrid-aware. The idea of a composite was first presented in [Bindel2017]. Composite algorithms retain some security even if one of their component algorithms is broken, which is discussed in detail in Section 9. This specification creates PQ/T Hybrids with the Module-Lattice-based Key Encapsulation Mechanism (ML-KEM), defined in [FIPS.203] as the PQ component. Instantiations of the composite ML-KEM scheme are provided based on ML-KEM, RSA-OAEP and ECDH. The full list of algorithms registered by this specification is in Section 6. Backwards compatibility in the sense of upgraded systems continuing to interoperate with legacy systems is not directly covered in this specification, but is the subject of Section 10.2.

Certain jurisdictions have recommended that ML-KEM be used exclusively within a PQ/T hybrid framework. The use of a composite scheme provides a straightforward implementation of hybrid solutions compatible with (and advocated by) some governments and cybersecurity agencies [BSI2021], [ANSSI2024].

In some situations it might be possible to add Post-Quantum, via a PQ/T Hybrid, to an already audited and compliant solution without invalidating the existing certification, whereas a full replacement of the traditional cryptography would almost certainly incur regulatory and compliance delays. In other words, PQ/T Hybrids can allow for deploying Post-Quantum Cryptography before the PQ modules and operational procedures are fully audited and certified. This, more than any other requirement, is what motivates the large number of algorithm combinations in this specification: The intention is to provide a stepping stone from which any cryptographic algorithm an organization has deployed today can evolve or transition.

While this specification registers a large number of composite algorithms, it is expected that organizations will choose to deploy a single composite algorithm, or a small number of composite algorithms, that meets the needs of their environment, and very few implementers will need concern themselves with the entire list. This specification does not specify any mandatory-to-implement algorithms, but Section 10.3 provides a short-list of recommended composite algorithms for common use-cases.

Composite ML-KEM is applicable in any PKIX-related application that would otherwise use ML-KEM.

1.1. Conventions and Terminology

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "NOT RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in BCP 14 [RFC2119] [RFC8174] when, and only when, they appear in all capitals, as shown here. These words may also appear in this document in lower case as plain English words, absent their normative meanings.

This specification is consistent with all terminology from [RFC9794]. In addition, the following terms are used in this specification:

ALGORITHM: The usage of the term "algorithm" within this specification generally refers to any function which has a registered Object Identifier (OID) for use within an ASN.1 AlgorithmIdentifier.

Application Backwards Compatibility: The usual definition of backwards compatibility, meaning whether an upgraded and non-upgraded application can successfully establish communication.

COMBINER: A combiner specifies how multiple shared secret keys are combined into a single shared secret key.

COMPOSITE CRYPTOGRAPHIC ELEMENT: [RFC9794] defines composites as: A cryptographic element that incorporates multiple component cryptographic elements of the same type in a multi-algorithm scheme.

COMPONENT / PRIMITIVE: The words "component" or "primitive" are used interchangeably to refer to a cryptographic algorithm that is used internally within a composite algorithm. For example this could be an asymmetric algorithm such as "ML-KEM-768" or "RSA-OAEP".

DER: Distinguished Encoding Rules as defined in [X.690].

ECDH: the Elliptic Curve Diffie-Hellman key agreement scheme defined in section 5.7.1.2 of [SP.800-56Ar3].

KEM: A key encapsulation mechanism as defined in Section 2.

PKI: Public Key Infrastructure, as defined in [RFC5280].

Post-Quantum Traditional (PQ/T) hybrid scheme: A multi-algorithm scheme where at least one component algorithm is a post-quantum algorithm and at least one is a traditional algorithm.

Protocol Backwards Compatibility: A property whereby a new feature can be added to a protocol without requiring any changes to the protocol’s specification and only minimal changes to its implementations (such as adding new identifiers). This is notable because many PQ/T Hybrids require modification of the protocol to make it "hybrid aware", whereas this specification presents as a standalone algorithm and thus can take advantage of existing cryptographic agility mechanisms.

ML-KEM: The Module-Lattice-based Key Encapsulation Mechanism algorithm defined in [FIPS.203]

RSA: The Rivest-Shamir-Adleman cryptosystem, used in this specification as the RSA-OAEP (Optimal Asymmetric Encryption Padding) scheme defined in [RFC8017].

SHARED SECRET KEY: A value established between two communicating parties for use as cryptographic key material suitable for direct use by symmetric cryptographic algorithms. This specification is concerned with shared secrets established via public key cryptographic operations.

X25519 and X448: The Edwards Curve Diffie-Hellman scheme defined in [RFC7748] with pramater sets X25519 and X448.

1.2. Notation

The algorithm descriptions use python-like syntax. The following symbols deserve special mention:

* || represents concatenation of two byte arrays.

* [:] represents byte array slicing.

* (a, b) represents a pair of values a and b. Typically this indicates that a function returns multiple values; the exact conveyance mechanism -- tuple, struct, output parameters, etc -- is left to the implementer.

* (a, _): represents a pair of values where one -- the second one in this case -- is ignored.

* Func<TYPE>(): represents a function that is parametrized by <TYPE> meaning that the function's implementation will have minor differences depending on the underlying TYPE. Typically this means that a function will need to look up different constants or use different underlying cryptographic primitives depending on which composite algorithm it is implementing.

1.3. Composite Design Philosophy

Composite algorithms, as defined in this specification, follow the definition in [RFC9794] and should be regarded as a single algorithm that performs a single cryptographic operation typical of a key establishment mechanism.This generally means that the complexity of combining algorithms can and should be handled by the cryptographic library or cryptographic module. The design intent is that protocols such as PKCS#10 [RFC2986], CMP [RFC9810], X.509 [RFC5280], the CMS [RFC5652], and the Trust Anchor Format [RFC5914] can treat composite algorithms as they would any other algorithm without the protocol layer to have any "hybrid-awareness". This is a property referred to as "protocol backwards-compatibility".

Discussion of the specific choices of algorithm pairings can be found in Section 6.2.

2. Overview of the Composite ML-KEM Scheme

Composite ML-KEM is a PQ/T hybrid Key Encapsulation Mechanism (KEM) which combines ML-KEM as specified in [FIPS.203] and [I-D.ietf-lamps-kyber-certificates] with one of RSA-OAEP defined in [RFC8017], the Elliptic Curve Diffie-Hellman key agreement schemes ECDH defined in section 5.7.1.2 of [SP.800-56Ar3], and X25519 / X448 defined in [RFC8410]. A KEM combiner function is used to combine the two component shared secret keys into a single shared secret key.

Composite Key Encapsulation Mechanisms are defined as cryptographic primitives that consist of three algorithms. These definitions are borrowed from [RFC9180].

* KeyGen() -> (pk, sk): A probabilistic key generation algorithm, which generates a public key pk and a secret key sk. Some cryptographic modules may also expose a KeyGen(seed) -> (pk, sk), which generates pk and sk deterministically from a seed. This specification assumes a seed-based keygen for ML-KEM.

* Encap(pk) -> (ss, ct): A probabilistic encapsulation algorithm, which takes as input a public key pk and outputs a ciphertext ct and shared secret key ss. Note: this specification uses Encap() to conform to [RFC9180], but [FIPS.203] uses Encaps().

* Decap(sk, ct) -> ss: A decapsulation algorithm, which takes as input a secret key sk and ciphertext ct and outputs a shared secret ss, or in some cases a distinguished error value. Note: this specification uses Decap() to conform to [RFC9180], but [FIPS.203] uses Decaps().

The KEM interface was chosen as the interface for a composite key establishment because it allows for arbitrary combinations of component algorithm types since both key transport and key agreement mechanisms can be promoted into KEMs as described in Section 2.1 and Section 2.2 below.

The following algorithms are defined for serializing and deserializing component values. These algorithms are inspired by similar algorithms in [RFC9180].

* SerializePublicKey(mlkemPK, tradPK) -> bytes: Produce a byte string encoding of the component public keys.

* DeserializePublicKey(bytes) -> (mlkemPK, tradPK): Parse a byte string to recover the component public keys.

* SerializeCiphertext(mlkemCT, tradCT) -> bytes: Produce a byte string encoding of the component ciphertexts.

* DeserializeCiphertext(bytes) -> (mlkemCT, tradCT): Parse a byte string to recover the component ciphertexts.

* SerializePrivateKey(mlkemSeed, tradSK) -> bytes: Produce a byte string encoding of the component private keys.

* DeserializePrivateKey(bytes) -> (mlkemSeed, tradSK): Parse a byte string to recover the component private keys.

Full definitions of serialization and deserialization algorithms can be found in Section 4.

2.1. Promotion of RSA-OAEP into a KEM

The RSA Optimal Asymmetric Encryption Padding (OAEP), as defined in section 7.1 of [RFC8017] is a public key encryption algorithm used to transport key material from a sender to a receiver. A "key transport" type algorithm has the following API:

* Encrypt(pk, ss) -> ct: Take an existing shared secret key ss and encrypt it for pk.

* Decrypt(sk, ct) -> ss: Decrypt the ciphertext ct to recover ss.

Note the difference between the API of RSA.Encrypt(pk, ss) -> ct and KEM.Encap(pk) -> (ss, ct) presented above. For this reason, RSA-OAEP cannot be directly combined with ML-KEM. Fortunately, a key transport mechanism such as RSA-OAEP can be easily promoted into a KEM by having the sender generate a random 256 bit shared secret key and encrypt it.

```
RSAOAEPKEM.Encap(pkR):
  shared_secret = SecureRandom(ss_len)
  enc = RSAES-OAEP-ENCRYPT(pkR, shared_secret)

  return shared_secret, enc
```

Note that the OAEP label L is left to its default value, which is the empty string as per [RFC8017]. The shared secret key output by the overall Composite ML-KEM already binds a composite KEM Combiner Label, so there is no need to also use the component Label.

The value of ss_len as well as concrete values for all the RSA-OAEP parameters used within this specification can be found in Section 6.1.

Decap(sk, ct) -> ss is accomplished by direct use of OAEP Decrypt.

```
RSAOAEPKEM.Decap(skR, enc):
  shared_secret = RSAES-OAEP-DECRYPT(skR, enc)

  return shared_secret
```

The encodings for the public key (pkR), private key (skR), and ciphertext (enc) are described in Section 4.

A quick note on the choice of RSA-OAEP as the supported RSA encryption primitive. RSA-KEM [RFC9690] is cryptographically robust and is more straightforward to work with, but it has fairly limited adoption and therefore is of limited value as a PQ migration mechanism. Also, while RSA-PKCS#1v1.5 [RFC8017] is still widely used, it is hard to make secure and no longer FIPS-approved as of the end of 2023 [SP800-131Ar2], so it is of limited forwards value. This leaves RSA-OAEP [RFC8017] as the remaining choice. See Section 6.2 for further discussion of algorithm choices.

Note that, at least at the time of writing, the algorithm RSAOAEPKEM is not defined as a standalone algorithm within PKIX standards and it does not have an assigned algorithm OID, so it cannot be used directly with CMS KEMRecipientInfo [RFC9629]; it is merely a building block for the composite algorithm.

2.2. Promotion of ECDH into a KEM

The elliptic curve Diffie-Hellman algorithm identified by the OID id-ecDH as defined in [RFC5480] and [SEC1] is a key agreement algorithm requiring both parties to contribute an asymmetric keypair to the derivation of the shared secret key. A "key agreement" type algorithm has the following API:

* DH(skX, pkY) -> ss: Each party combines their secret key skX with the other party’s public key pkY.

Note the difference between the API of DH(skX, pkY) -> ss and KEM.Encap(pk) -> (ss, ct) presented above. For this reason, a Diffie-Hellman key exchange cannot be directly combined with ML-KEM. Fortunately, a Diffie-Hellman key agreement can be easily promoted into a KEM Encap(pk) -> (ss, ct) by having the sender generate an ephemeral keypair for themself and sending their public key as the ciphertext ct. Composite ML-KEM uses a simplified version of the DHKEM definition from [RFC9180]:

```
DHKEM.Encap(pkR):
  (skE, pkE) = GenerateKeyPair()
  ss = DH(skE, pkR)
  ct = SerializePublicKey(pkE)

  return ss, ct
```

Decap(sk, ct) -> ss is accomplished in the analogous way.

```
DHKEM.Decap(skR, ct):
  pkE = DeserializePublicKey(ct)
  ss = DH(skR, pkE)

  return ss
```

This construction applies for all variants of elliptic curve Diffie-Hellman used in this specification: ECDH, X25519, and X448.

For ECDH, DH() yields the value Z as described in section 5.7.1.2 of [SP.800-56Ar3].

For X25519 and X448, DH() yields the value K as described in section 6 of [RFC7748].

The encodings for the public key (pkR), private key (skR), and ciphertext (pkE) are described in Section 4.

The promotion of DH to a KEM is similar to the DHKEM functions in [RFC9180], but it is simplified in the following ways:

1. Notation has been aligned to the notation used in this specification.

2. Since a KEM Combiner Label is included explicitly in the Composite ML-KEM combiner, there is no need to perform the labeled steps of ExtractAndExpand().

3. Since the ciphertext and receiver’s public key are included explicitly in the Composite ML-KEM combiner, there is no need to construct the kem_context object.

Note that here, SerializePublicKey() and DeserializePublicKey() refer to the underlying encoding of the DH primitive, and not to the composite serialization functions defined in Section 4.

Note that, at least at the time of writing, the algorithm DHKEM is not defined as a standalone algorithm within PKIX standards and it does not have an assigned algorithm OID, so it cannot be used directly with CMS KEMRecipientInfo [RFC9629]; it is merely a building block for the composite algorithm.

3. Composite ML-KEM Functions

This section describes the composite ML-KEM functions needed to instantiate the public API of a Key Encapsulation Mechanism as defined in Section 2.

3.1. Key Generation

In order to maintain security properties of the composite, this specification strictly forbids re-using component key material between composite and non-composite keys, or between multiple composite keys. This means that an invocation of Composite-ML-KEM.KeyGen() MUST perform, or otherwise guarantee, fresh generation of the key material for both underlying algorithms and MUST NOT reuse existing key material. See Section 9.3 for a discussion.

To generate a new keypair for composite schemes, the KeyGen() -> (pk, sk) function is used. The KeyGen() function calls the two key generation functions of the component algorithms independently. Multi-threaded, multi-process, or multi-module applications might choose to execute the key generation functions in parallel for better key generation performance or architectural modularity.

To generate an ML-KEM key pair this specification uses the function ML-KEM.KeyGen_internal(d, z). According to [FIPS.203] d and z are two random 32 Byte values. This document combines both values in mlkemSeed by concatenating them so that mlkemSeed = d || z.

The following describes how to instantiate a KeyGen() function for a given composite algorithm represented by <OID>.

```
Composite-ML-KEM<OID>.KeyGen() -> (pk, sk)

Explicit Inputs:
     None

Implicit Inputs mapped from <OID>:

  ML-KEM     The underlying ML-KEM algorithm and
             parameter set, for example "ML-KEM-768".

  Trad       The underlying traditional algorithm and
             parameter, for example "RSA-OAEP"
             or "X25519".

Output:
  (pk, sk)  The composite keypair.

Key Generation Process:

  1. Generate component keys

    mlkemSeed = Random(64)
    (mlkemPK, mlkemSK) = ML-KEM.KeyGen_internal(mlkemSeed[:32], mlkemSeed[32:])
    (tradPK, tradSK) = Trad.KeyGen()

  2. Check for component key gen failure
    if NOT (mlkemPK, mlkemSK) or NOT (tradPK, tradSK):
      output "Key generation error"

  3. Output the composite public and private keys

    pk = SerializePublicKey(mlkemPK, tradPK)
    sk = SerializePrivateKey(mlkemSeed, tradSK)
    return (pk, sk)
```

In order to ensure fresh keys, the key generation functions MUST be executed for both component algorithms. Compliant parties MUST NOT use, import or export component keys that are used in other contexts, combinations, or by themselves as keys for standalone algorithm use. For more details on the security considerations around key reuse, see Section 9.3.

Errors produced by the component KeyGen() routines MUST be forwarded on to the calling application. Further discussion can be found below in Section 3.5.

3.1.1. Allowed Modifications to the Key Generation Process

Key generation is a process that is entirely internal to a cryptographic module, and as such it is often customized to fit the performance or operational requirements of the module. In cases where the private keys never leave the module or are otherwise not required to interoperate with other cryptographic modules, it is not required for interoperability for the private keys to match the format described in this specification. Therefore, in general, implementations of Composite ML-KEM MAY use an alternate key generation process so long as it generates compatible public keys, and so long as both component keys are freshly-generated and not re-used in a standalone key or within another composite key. Below are some examples of modifications that an implementer MAY make to the key generation process.

Implementations MAY modify this process to additionally output the expanded mlkemSK or to make use of ML-KEM.KeyGen_internal(d, z) as needed to expand the ML-KEM seed (d || z) into an expanded key prior to performing a signing operation.

In cases where it is desirable to have a deterministic KeyGen of one or both component keys from a seed, this process MAY be modified to expose an interface of Composite-ML-KEM<OID>.KeyGen(seed) such that one component algorithm is generated from the seed and the other from random, or the input seed is cryptohraphically expanded to produce seeds for both components. Security analysis of such a modified key generation process is outside the scope of this document.

Where interoperable private keys are not required, implementations MAY choose to use a different private key representation than the one given in Section 4.2. For example, the component keys MAY be stored in separate cryptographic modules, or MAY be stored in separate PKCS#8 objects, or MAY be stored in a format that preserves the ML-KEM expanded key instead of the ML-KEM seed. The required modifications to the key generation process, as well as the signature generation process below, to support these private key representations are considered compliant with this specification so long as they generate compatible public keys, and so long as both component keys are freshly-generated. Note that when implementing Composite ML-KEM with a private key format that does not preserve the ML-KEM seed, especially when implementing on top of a cryptographic module that does not support seeds, it will be impossible to reconstruct a compliant seed-based private key as described in Section 4.2

3.2. Encapsulation

The Encap(pk) of a Composite ML-KEM algorithm is designed to behave exactly the same as ML-KEM.Encaps(ek) defined in Algorithm 20 in Section 7.2 of [FIPS.203]. Specifically, Composite-ML-KEM.Encap(pk) produces a 256-bit shared secret key that can be used directly with any symmetric-key cryptographic algorithm. In this way, Composite ML-KEM can be used as a direct drop-in replacement anywhere that ML-KEM is used.

The following describes how to instantiate a Encap(pk) function for a given composite algorithm represented by <OID>.

```
Composite-ML-KEM<OID>.Encap(pk) -> (ss, ct)

Explicit Inputs:

  pk      Composite public key consisting of encryption public keys
          for each component.

Implicit inputs mapped from <OID>:

  ML-KEM  The underlying ML-KEM algorithm and
          parameter set, for example "ML-KEM-768".

  Trad    The underlying ML-KEM algorithm and
          parameter set, for example "RSA-OAEP"
          or "X25519".

  Label   KEM Combiner Label value for binding the ciphertext to the
          Composite OID. See section on KEM Combiner Labels below.

Output:

  ss      The shared secret key, a 256-bit key suitable for use with
          symmetric cryptographic algorithms.

  ct      The ciphertext, a byte string.

Encap Process:

  1. Separate the public keys.

      (mlkemPK, tradPK) = DeserializePublicKey(pk)

  2.  Perform the respective component Encap operations according to
      their algorithm specifications.
```

```
(mlkemCT, mlkemSS) = ML-KEM.Encaps(mlkemPK)
(tradCT, tradSS) = TradKEM.Encap(tradPK)
```

3. If either ML-KEM.Encaps() or TradKEM.Encap() return an error, then this process must return an error.

```
if NOT (mlkemCT, mlkemSS) or NOT (tradCT, tradSS):
  output "Encapsulation error"
```

4. Encode the ciphertext

```
ct = SerializeCiphertext(mlkemCT, tradCT)
```

5. Combine the KEM secrets and additional context to yield the composite shared secret key.

```
ss = KemCombiner(mlkemSS, tradSS, tradCT, tradPK, Label)
```

6. Output composite shared secret key and ciphertext.

```
return (ss, ct)
```

The specific values for Label are defined per Composite ML-KEM algorithm in Section 6.

Errors produced by the component Encaps() routines MUST be forwarded on to the calling application. Further discussion can be found below in Section 3.5.

3.3. Decapsulation

The Decap(sk, ct) -> ss of a Composite ML-KEM algorithm is designed to behave exactly the same as ML-KEM.Decaps(dk, c) defined in Algorithm 21 in Section 7.3 of [FIPS.203]. Specifically, Composite-ML-KEM.Decap(sk, ct) produces a 256-bit shared secret key that can be used directly with any symmetric-key cryptographic algorithm. In this way, Composite ML-KEM can be used as a direct drop-in replacement anywhere that ML-KEM is used.

The following describes how to instantiate a Decap(sk, ct) function for a given composite algorithm represented by <OID>.

```
Composite-ML-KEM<OID>.Decap(sk, ct) -> ss
```

Explicit inputs

sk   Composite private key consisting of decryption private keys for each component.

ct The ciphertext, a byte string.

Implicit inputs mapped from <OID>:

ML-KEM The underlying ML-KEM algorithm and parameter set, for example "ML-KEM-768".

Trad The underlying traditional algorithm and parameter set, for example "RSA-OAEP" or "X25519".

Label KEM Combiner Label value for binding the ciphertext to the Composite ML-KEM OID. See section on KEM Combiner Labels below.

Implicit inputs looked up from SK:

tradPK The traditional public key is required for the KEM combiner. For discussion of where to get this value, see the Decapsulation Requires the Public Key section.

Output:

ss The shared secret key, a 256-bit key suitable for use with symmetric cryptographic algorithms.

Decap Process:

1. Separate the private keys and ciphertexts

```
(mlkemSeed, tradSK) = DeserializePrivateKey(sk)
(_, mlkemSK) = ML-KEM.KeyGen(mlkemSeed[:32], mlkemSeed[32:])
(mlkemCT, tradCT) = DeserializeCiphertext(ct)
```

2. Perform the respective component Decap operations according to their algorithm specifications.

```
mlkemSS = ML-KEM.Decaps(mlkemSK, mlkemCT)
tradSS  = TradKEM.Decap(tradSK, tradCT)
```

3. If either ML-KEM.Decaps() or TradKEM.Decap() return an error, then this process must return an error.

```
if NOT mlkemSS or NOT tradSS:
  output "Decapsulation error"
```

4. Combine the KEM secrets and additional context to yield the

composite shared secret key.

```
ss = KemCombiner(mlkemSS, tradSS, tradCT, tradPK, Label)
```

5. Output composite shared secret key.

```
return ss
```

Steps 2 and 4 SHOULD be performed in a timing-invariant way to prevent side-channel attackers from learning any of the inputs or output of the KEM combiner.

Step 4 requires the Decaps() process to have access to tradPK, which is not carried in the private key format and therefore the implementation is required to acquire it from some out-of-band means. The Implementation Considerations Section 10.4 provides further discussion on this.

It is possible to use component private keys stored in separate software or hardware keystores. Variations in the process to accommodate particular private key storage mechanisms are considered to be conformant to this specification so long as it produces the same output and error handling as the process sketched above.

In order to properly achieve its security properties, the KEM combiner requires that all inputs are fixed-length or length-encoded. Since each Composite ML-KEM algorithm fully specifies its component algorithms, including key sizes, all inputs should be fixed-length in non-error scenarios except for minor variations introduced by encoding. In the cases where there are minor variations introduced by encoding, those encodings already have a fixed-length prefix followed by length-encoded data, so the requirements for the KEM combiner security properties hold (namely that the input is injective). However some implementations may choose to perform additional checking to handle certain error conditions. In particular, the KEM combiner step should not be performed if either of the component decapsulations returned an error condition indicating malformed inputs. RSA-based composites MUST ensure that the modulus size (i.e. the size of tradCT and tradPK) matches that specified for the given Composite ML-KEM algorithm in Section 6; depending on the cryptographic library used, this check may be done by the library or may require an explicit check as part of the Composite-ML-KEM.Decap() routine. Implementers should keep in mind that some instances of tradCT and tradPK will be DER-encoded which could introduce minor length variations such as dropping leading zeroes; since the underlying KEMs are assumed to be IND-CCA secure, decapsulation against tampered ciphertexts or public keys is assumed to fail, these length differences are considered benign to the KEM combiner.

Errors produced by the component Decaps() routines MUST be forwarded on to the calling application. Further discussion can be found below in Section 3.5.

3.4. KEM Combiner Function

This specification provides a combiner construction with SHA3-256 for all combinations of algorithms.

```
KemCombiner(mlkemSS, tradSS, tradCT, tradPK, Label) -> ss
```

Explicit inputs:

The list of input values to be combined.

Output:

ss The shared secret key, a 256-bit key suitable for use with symmetric cryptographic algorithms.

Process:

```
ss = SHA3-256(mlkemSS || tradSS || tradCT || tradPK || Label)

return ss
```

3.5. Error Handling and Explicit Rejection

ML-KEM, particularly its Decaps() defined in Algorithms 18 and 21 of [FIPS.203], is designed to be implicitly rejecting, meaning that a failure within the underlying PKE scheme due to a mangled ciphertext will not cause ML-KEM.Decaps() to return an error, but instead any errors encountered during decapsulation are handled by producing a pseudo-random shared secret. ML-KEM.Decaps() can, however return errors for example if the provided ciphertext or decapsulation private key is the wrong size.

In Composite ML-KEM, not all component algorithms will be implicitly rejecting, for example RSA-OAEP’s Decrypt() can return an error if the padding is incorrect. In general, in the case that one of the component primitives generates an error during Composite ML-KEM KeyGen, Encaps, or Decaps, Composite ML-KEM MUST clear all buffers containing key material and forward the error to its caller; i.e. Composite ML-KEM MUST be explicitly rejecting whenever one of its components is. The same applies to Composite ML-KEM KeyGen() and Encaps(): Composite KEM MUST forward any errors produced by component algorithms.

4. Serialization

This section presents routines for serializing and deserializing composite public keys, private keys, and ciphertext values to bytes. The functions defined in this section are considered internal implementation details and are referenced from within the public API definitions in Section 3.

Deserialization is possible because ML-KEM has fixed-length public keys, private keys (seeds), and ciphertext values as shown in the following table.

Algorithm	Public Key	Private Key	Ciphertext
ML-KEM-768	1184	64	1088
ML-KEM-1024	1568	64	1568

Table 1: ML-KEM Sizes in bytes

For all serialization routines below, when these values are required to be carried in an ASN.1 structure, they are wrapped as described in Section 5.1.

While ML-KEM has a single fixed-size representation for each of public key, private key, and ciphertext, the traditional component might allow multiple valid encodings; for example an elliptic curve public key, and therefore also ciphertext, might be validly encoded as either compressed or uncompressed [SEC1], or an RSA private key could be encoded in Chinese Remainder Theorem form [RFC8017]. In order to obtain interoperability, composite algorithms MUST use the following encodings of the underlying components:

* *ML-KEM*: MUST be encoded as specified in sections 7.1 and 7.2 of [FIPS.203], using a 64-byte seed (d || z) as the private key.

* *RSA*: the public key MUST be encoded as RSAPublicKey with the (n,e) public key representation as specified in A.1.1 of [RFC8017] and the private key representation as RSAPrivateKey specified in A.1.2 of [RFC8017] with version 0 and 'otherPrimeInfos' absent. An RSA-OAEP ciphertext MUST be encoded as specified in section 7.1.1 of [RFC8017]

* *ECDH*: public key MUST be encoded as an uncompressed elliptic curve point as in section 2.2 of [RFC5480], including the leading byte 0x04 indicating uncompressed encoding and without the ASN.1 OCTET STRING wrapper. This is consistent with the encoding of EC public keys in X9.62 [X9.62_2005]. The private key MUST be encoded as ECPrivateKey specified in [RFC5915] with 'NamedCurve' parameter set to the OID of the curve, but without the 'publicKey' field. The ciphertext MUST be encoded in the same manner as the public key.

* *X25519 and X448*: the public key MUST be encoded as per section 5 of [RFC7748] and the private key is a 32 or 56 byte raw value for X25519 and X448 respectively. The ciphertext MUST be encoded in the same manner as the public key.

All ASN.1 objects SHALL be encoded using DER on serialization.

Even with fixed encodings for the traditional component, there may be slight differences in size of the encoded value due to, for example, encoding rules that drop leading zeroes. See Appendix A for further discussion of encoded size of each composite algorithm.

The deserialization routines described below do not check for well-formedness of the cryptographic material they are recovering. It is assumed that underlying cryptographic primitives will catch malformed values and raise an appropriate error.

4.1. SerializePublicKey and DeserializePublicKey

The serialization routine for keys simply concatenates the public keys of the component algorithms, as defined below:

```
Composite-ML-KEM.SerializePublicKey(mlkemPK, tradPK) -> bytes
```

Explicit inputs:

mlkemPK The ML-KEM public key, which is bytes.

tradPK The traditional public key in the appropriate encoding for the underlying component algorithm.

Implicit inputs:

None

Output:

bytes The encoded composite public key.

Serialization Process:

1. Combine and output the encoded public key

```
output mlkemPK || tradPK
```

Deserialization reverses this process. Each component key is deserialized according to their respective specification as shown in Appendix B.

The following describes how to instantiate a DeserializePublicKey(bytes) function for a given composite algorithm represented by <OID>.

```
Composite-ML-KEM<OID>.DeserializePublicKey(bytes) -> (mlkemPK, tradPK)

Explicit inputs:

  bytes   An encoded composite public key.

Implicit inputs mapped from <OID>:

  ML-KEM   The underlying ML-KEM algorithm and
           parameter, for example, could be "ML-KEM-768".

Output:

  mlkemPK  The ML-KEM public key, which is bytes.

  tradPK   The traditional public key in the appropriate
           encoding for the underlying component algorithm.


Deserialization Process:

  1. Parse each constituent encoded public key.
       The length of the mlkemPK is known based on the size of
       the ML-KEM component key length specified by the Object ID.

     switch ML-KEM do
        case ML-KEM-768:
          mlkemPK = bytes[:1184]
          tradPK  = bytes[1184:]
        case ML-KEM-1024:
          mlkemPK = bytes[:1568]
          tradPK  = bytes[1568:]

     Note that while ML-KEM has fixed-length keys, RSA
     may not, depending on encoding, so rigorous length-checking
     of the overall composite key is not always possible.

  2. Output the component public keys

     output (mlkemPK, tradPK)
```

4.2. SerializePrivateKey and DeserializePrivateKey

The serialization routine for keys simply concatenates the private keys of the component algorithms, as defined below:

```
Composite-ML-KEM.SerializePrivateKey(mlkemSeed, tradSK) -> bytes

Explicit inputs:

  mlkemSeed  The ML-KEM private key, which consists of 32 Byte seed value d
             concatenated with 32 Byte seed value z.

  tradSK     The traditional private key in the appropriate
             encoding for the underlying component algorithm.

Implicit inputs:

  None

Output:

  bytes   The encoded composite private key.

Serialization Process:

  1. Combine and output the encoded private key.

     output mlkemSeed || tradSK
```

Deserialization reverses this process. Each component key is deserialized according to their respective specification as shown in Appendix B.

The following describes how to instantiate a DeserializePrivateKey(bytes) function. Since ML-KEM private keys are 64 bytes for all parameter sets, this function does not need to be parametrized.

```
Composite-ML-KEM.DeserializePrivateKey(bytes)
                                    -> (mlkemSeed, tradSK)

Explicit inputs:

  bytes   An encoded composite private key.

Implicit inputs:

  That an ML-KEM private key is 64 bytes for all parameter sets.

Output:

  mlkemSeed  The ML-KEM private key, which consists of 32 Byte seed value d
             concatenated with 32 Byte seed value z.

  tradSK    The traditional private key in the appropriate
             encoding for the underlying component algorithm.


Deserialization Process:

  1. Parse the ML-KEM seed, which is always a 64 byte seed
     for all parameter sets.

     mlkemSeed = bytes[:64]
     tradSK    = bytes[64:]

  2. Output the component private keys

     output (mlkemSeed,tradSK)
```

4.3. SerializeCiphertext and DeserializeCiphertext

The serialization routine for the composite ciphertext value simply concatenates the fixed-length ML-KEM ciphertext with the ciphertext from the traditional algorithm, as defined below:

Composite-ML-KEM.SerializeCiphertext(mlkemCT, tradCT) -> bytes

Explicit inputs:

mlkemCT The ML-KEM ciphertext, which is bytes.

tradCT The traditional ciphertext in the appropriate encoding for the underlying component algorithm.

Implicit inputs:

None

Output:

bytes The encoded composite ciphertext value.

Serialization Process:

1. Combine and output the encoded composite ciphertext

   output mlkemCT || tradCT

Deserialization reverses this process. Each component ciphertext is deserialized according to their respective specification as shown in Appendix B.

The following describes how to instantiate a DeserializeCiphertext(bytes) function for a given composite algorithm represented by <OID>.

```
Composite-ML-KEM<OID>.DeserializeCiphertext(bytes)
                                          -> (mlkemCT, tradCT)
```

Explicit inputs:

bytes   An encoded composite ciphertext value.

Implicit inputs mapped from <OID>:

ML-KEM   The underlying ML-KEM algorithm and parameter, for example, could be "ML-KEM-768".

Output:

mlkemCT The ML-KEM ciphertext, which is bytes.

tradCT   The traditional ciphertext in the appropriate encoding for the underlying component algorithm.

Deserialization Process:

1. Parse each constituent encoded ciphertext. The length of the mlkemCT is known based on the size of the ML-KEM component ciphertext length specified by the Object ID.

```
switch ML-KEM do
   case ML-KEM-768:
     mlkemCT = bytes[:1088]
     tradCT  = bytes[1088:]
   case ML-KEM-1024:
     mlkemCT= bytes[:1568]
     tradCT  = bytes[1568:]
```

2. Output the component ciphertext values

```
output (mlkemCT, tradCT)
```

5. Use within X.509 and PKIX

The following sections provide processing logic and the necessary ASN.1 modules necessary to use composite ML-KEM within X.509 and PKIX protocols. Use within the Cryptographic Message Syntax (CMS) will be covered in a separate specification.

While composite ML-KEM keys and ciphertext values MAY be used raw, the following sections provide conventions for using them within X.509 and other PKIX protocols such that Composite ML-KEM can be used as a drop-in replacement for KEM algorithms in PKCS#10 [RFC2986], CMP [RFC9810], X.509 [RFC5280], and related protocols.

5.1. Encoding to DER

The serialization routines presented in Section 4 produce raw binary values. When these values are required to be carried within a DER-encoded message format such as an X.509's subjectPublicKey or a OneAsymmetricKey.privateKey OCTET STRING [RFC5958], then the BIT STRING or OCTET STRING contains this raw byte string output of the appropriate serialization routine from Section 4 without further encoding.

When a Composite ML-KEM public key appears outside of a SubjectPublicKeyInfo type in an environment that uses ASN.1 encoding, it could be encoded as an OCTET STRING by using the Composite-ML-KEM-PublicKey type defined below.

```
Composite-ML-KEM-PublicKey ::= OCTET STRING
```

Size constraints MAY be enforced, as appropriate as per Appendix A.

5.2. Key Usage Bits

When any Composite ML-KEM Object Identifier appears within the SubjectPublicKeyInfo.AlgorithmIdentifier field of an X.509 certificate [RFC5280], the key usage certificate extension MUST only contain:

keyEncipherment

Composite ML-KEM keys MUST NOT be used in a "dual usage" mode because even if the traditional component key supports both signing and encryption, the post-quantum algorithms do not and therefore the overall composite algorithm does not. Implementations MUST NOT use one component of the composite for the purposes of digital signature and the other component for the purposes of encryption or key establishment.

5.3. ASN.1 Definitions

Composite ML-KEM uses a substantially non-ASN.1 based encoding, as specified in Section 4. However, as composite algorithms will be used within ASN.1-based X.509 and PKIX protocols, some conventions for ASN.1 wrapping are necessary.

The following ASN.1 Information Object Classes are defined to allow for compact definitions of each composite algorithm, leading to a smaller overall ASN.1 module.

```
pk-CompositeKEM {OBJECT IDENTIFIER:id}
  PUBLIC-KEY ::= {
    IDENTIFIER id
    -- KEY no ASN.1 wrapping --
    PARAMS ARE absent
    CERT-KEY-USAGE { keyEncipherment }
    -- PRIVATE-KEY no ASN.1 wrapping --
  }

kema-CompositeKEM {
  OBJECT IDENTIFIER:id,
    PUBLIC-KEY:publicKeyType }
    KEM-ALGORITHM ::= {
         IDENTIFIER id
         -- VALUE no ASN.1 wrapping --
         PARAMS ARE absent
         PUBLIC-KEYS { publicKeyType }
         SMIME-CAPS { IDENTIFIED BY id }
        }
```

Figure 1: ASN.1 Object Information Classes for Composite ML-KEM

As an example, the public key and KEM algorithm types associated with id-MLKEM768-ECDH-P256-SHA3-256 are defined as:

```
pk-MLKEM768-ECDH-P256-SHA3-256 PUBLIC-KEY ::=
  pk-CompositeKEM {
    id-MLKEM768-ECDH-P256-SHA3-256 }

kema-MLKEM768-ECDH-P256-SHA3-256 KEM-ALGORITHM ::=
    kema-CompositeKEM{
      id-MLKEM768-ECDH-P256-SHA3-256,
      pk-MLKEM768-ECDH-P256-SHA3-256 }
```

The full set of key types defined by this specification can be found in the ASN.1 Module in Section 7.

Use cases that require an interoperable encoding for composite private keys will often need to place a composite private key inside a OneAsymmetricKey structure defined in [RFC5958], such as when private keys are carried in PKCS #12 [RFC7292], CMP [RFC9810] or CRMF [RFC4211]. The definition of OneAsymmetricKey is copied here for convenience:

```
    OneAsymmetricKey ::= SEQUENCE {
          version                   Version,
          privateKeyAlgorithm       PrivateKeyAlgorithmIdentifier,
          privateKey                PrivateKey,
          attributes            [0] Attributes OPTIONAL,
          ...,
          [[2: publicKey        [1] PublicKey OPTIONAL ]],
          ...
        }

     ...
     PrivateKey ::= OCTET STRING
                           -- Content varies based on type of key.  The
                           -- algorithm identifier dictates the format of
                           -- the key.
```

Figure 2: OneAsymmetricKey as defined in [RFC5958]

When a composite private key is conveyed inside a OneAsymmetricKey structure (version 1 of which is also known as PrivateKeyInfo) [RFC5958], the privateKeyAlgorithm field SHALL be set to the corresponding composite algorithm identifier defined according to Section 6 and its parameters field MUST be absent. The privateKey field SHALL contain the OCTET STRING representation of the serialized composite private key as per Section 4.2. The publicKey field remains OPTIONAL. If the publicKey field is present, it MUST be a composite public key as per Section 4.1.

Some applications might need to reconstruct the SubjectPublicKeyInfo or OneAsymmetricKey objects corresponding to each component key individually, for example if this is required for invoking the underlying primitive. Section 6 provides the necessary mapping between composite and their component algorithms for doing this reconstruction.

Component keys of a composite private key MUST NOT be used in any other type of key or as a standalone key. For more details on the security considerations around key reuse, see Section 9.3.

6. Algorithm Identifiers and Parameters

This section lists the algorithm identifiers and parameters for all Composite ML-KEM algorithms.

Full specifications for the referenced algorithms can be found in Appendix B.

As the number of algorithms can be daunting to implementers, see Section 10.3 for a discussion of choosing a subset to support.

Each Composite ML-KEM algorithm has a unique Label which is used in constructing the KEM combiner in (Section 3.4). This helps protect against a different algorithm arriving at the same shared secret key even if all inputs are the same.

Label values are provided in two forms: where the label value is alphanumeric ASCII, they are represented below as strings. For example, "MLKEM768-RSAOAEP2048" below is equivalent to the hexadecimal value 4D4C4B454D3736382D5253414F41455032303438.

Some of the label values contain problematic characters, such as backslashes, that can cause issues displaying correctly in rendered documents or even in source code when the compiler interprets it as an escape character. Below, these are represented directly in hexadecimal. For example, the label for id-MLKEM768-X25519-SHA3-256 is "\.//^\", but to avoid transcription errors it is provided only in hexadecimal as 5c2e2f2f5e5c.

Composite KEM algorithm list:

* id-MLKEM768-RSA2048-SHA3-256
  - OID: 1.3.6.1.5.5.7.6.55
  - Label: "MLKEM768-RSAOAEP2048"
  - ML-KEM variant: ML-KEM-768
  - Traditional Algorithm: RSA
    - o Traditional KEM Algorithm: id-RSAES-OAEP
    - o RSA size: 2048
    - o RSAES-OAEP parameters: See Table 2
* id-MLKEM768-RSA3072-SHA3-256
  - OID: 1.3.6.1.5.5.7.6.56
  - Label: "MLKEM768-RSAOAEP3072"
  - ML-KEM variant: ML-KEM-768
  - Traditional Algorithm: RSA

      o Traditional KEM Algorithm: id-RSAES-OAEP

      o RSA size: 3072

      o RSAES-OAEP parameters: See Table 2

* id-MLKEM768-RSA4096-SHA3-256

  - OID: 1.3.6.1.5.5.7.6.57

  - Label: "MLKEM768-RSAOAEP4096"

  - ML-KEM variant: ML-KEM-768

  - Traditional Algorithm: RSA

    o Traditional KEM Algorithm: id-RSAES-OAEP

    o RSA size: 4096

    o RSAES-OAEP parameters: See Table 2

* id-MLKEM768-X25519-SHA3-256

  - OID: 1.3.6.1.5.5.7.6.58

  - Label: "5c2e2f2f5e5c" (hex)

  - ML-KEM variant: ML-KEM-768

  - Traditional Algorithm: X25519

    o Traditional KEM Algorithm: id-X25519

* id-MLKEM768-ECDH-P256-SHA3-256

  - OID: 1.3.6.1.5.5.7.6.59

  - Label: "MLKEM768-P256"

  - ML-KEM variant: ML-KEM-768

  - Traditional Algorithm: ECDH

    o Traditional KEM Algorithm: id-ecDH

    o ECDH curve: secp256r1

* id-MLKEM768-ECDH-P384-SHA3-256
  - OID: 1.3.6.1.5.5.7.6.60
  - Label: "MLKEM768-P384"
  - ML-KEM variant: ML-KEM-768
  - Traditional Algorithm: ECDH
    o Traditional KEM Algorithm: id-ecDH
    o ECDH curve: secp384r1
* id-MLKEM768-ECDH-brainpoolP256r1-SHA3-256
  - OID: 1.3.6.1.5.5.7.6.61
  - Label: "MLKEM768-BP256"
  - ML-KEM variant: ML-KEM-768
  - Traditional Algorithm: ECDH
    o Traditional KEM Algorithm: id-ecDH
    o ECDH curve: brainpoolP256r1
* id-MLKEM1024-RSA3072-SHA3-256
  - OID: 1.3.6.1.5.5.7.6.62
  - Label: "MLKEM1024-RSAOAEP3072"
  - ML-KEM variant: ML-KEM-1024
  - Traditional Algorithm: RSA
    o Traditional KEM Algorithm: id-RSAES-OAEP
    o RSA size: 3072
    o RSAES-OAEP parameters: See Table 2
* id-MLKEM1024-ECDH-P384-SHA3-256
  - OID: 1.3.6.1.5.5.7.6.63

- Label: "MLKEM1024-P384"
- ML-KEM variant: ML-KEM-1024
- Traditional Algorithm: ECDH
  - Traditional KEM Algorithm: id-ecDH
  - ECDH curve: secp384r1

* id-MLKEM1024-ECDH-brainpoolP384r1-SHA3-256
  - OID: 1.3.6.1.5.5.7.6.64
  - Label: "MLKEM1024-BP384"
  - ML-KEM variant: ML-KEM-1024
  - Traditional Algorithm: ECDH
    - Traditional KEM Algorithm: id-ecDH
    - ECDH curve: brainpoolP384r1
* id-MLKEM1024-X448-SHA3-256
  - OID: 1.3.6.1.5.5.7.6.65
  - Label: "MLKEM1024-X448"
  - ML-KEM variant: ML-KEM-1024
  - Traditional Algorithm: X448
    - Traditional KEM Algorithm: id-X448
* id-MLKEM1024-ECDH-P521-SHA3-256
  - OID: 1.3.6.1.5.5.7.6.66
  - Label: "MLKEM1024-P521"
  - ML-KEM variant: ML-KEM-1024
  - Traditional Algorithm: ECDH
    - Traditional KEM Algorithm: id-ecDH

- ECDH curve: secp521r1

In alignment with ML-KEM [FIPS.203], Composite KEM algorithms output a 256-bit shared secret key at all security levels.

For all RSA key types and sizes, the exponent is RECOMMENDED to be 65537. Implementations MAY support only 65537 and reject other exponent values. Legacy RSA implementations that use other values for the exponent MAY be used within a composite, but need to be careful when interoperating with other implementations.

SHA3-256 is used as the KDF for all Composite ML-KEM algorithms.

6.1. RSA-OAEP Parameters

Use of RSA-OAEP [RFC8017] requires additional parameters to be specified.

The RSA component keys MUST be generated at the specified 2048-bit, 3072-bit, 4096-bit key sizes respectively (up to small differences such as dropping leading zeros); intermediate sizes are not acceptable.

As with the other Composite ML-KEM algorithms, AlgorithmIdentifier parameters MUST be absent. The RSA-OAEP primitive SHALL be instantiated with the following hard-coded parameters which are the same for the 2048, 3072 and 4096 bit key sizes since the objective is to carry and output a 256-bit shared secret key at all security levels.

RSAES-OAEP-params	Value
hashAlgorithm	id-sha256
MaskGenAlgorithm.algorithm	id-mgf1
maskGenAlgorithm.parameters	id-sha256
pSourceAlgorithm	pSpecifiedEmpty
ss_len	256 bits

Table 2: RSA-OAEP Parameters

Full specifications for the referenced algorithms can be found in Appendix B.

Note: The mask length, according to [RFC8017], is k - hLen - 1, where k is the size of the RSA modulus. Since the choice of hash function and the RSA key size is fixed for each composite algorithm, implementations could choose to pre-compute and hard-code the mask length.

6.2. Rationale for choices

In generating the list of composite algorithms, the idea was to provide composite algorithms at various security levels with varying performance characteristics.

The main design consideration in choosing pairings is to prioritize providing pairings of each ML-KEM security level with commonly-deployed traditional algorithms. This supports the design goal of using composites as a stepping stone to efficiently deploy post-quantum on top of existing hardened and certified traditional algorithm implementations. This was prioritized rather than attempting to exactly match the security level of the post-quantum and traditional components -- which in general is difficult to do since there is no academic consensus on how to compare the "bits of security" against classical attackers and "qubits of security" against quantum attackers.

While it may seem odd to use 256-bit outputs at all security levels, this aligns with ML-KEM [FIPS.203] which produces a 256-bit shared secret key at all security levels. SHA3-256 has 256 bits of (2nd) pre-image resistance, which is the required property for a KDF to provide 128 bits of security, as allowed in Table 3 of [SP.800-57pt1r5].

7. ASN.1 Module

```
<CODE STARTS>

Composite-MLKEM-2025
      { iso(1) identified-organization(3) dod(6) internet(1)
        security(5) mechanisms(5) pkix(7) id-mod(0)
        id-mod-composite-mlkem-2025(TBDMOD) }

DEFINITIONS IMPLICIT TAGS ::= BEGIN

EXPORTS ALL;

IMPORTS

PUBLIC-KEY, AlgorithmIdentifier{}, SMIME-CAPS
  FROM AlgorithmInformation-2009  -- RFC 5912 [X509ASN1]
```

```
         { iso(1) identified-organization(3) dod(6) internet(1)
           security(5) mechanisms(5) pkix(7) id-mod(0)
           id-mod-algorithmInformation-02(58) }

   KEM-ALGORITHM
     FROM KEMAlgorithmInformation-2023
         { iso(1) identified-organization(3) dod(6) internet(1)
           security(5) mechanisms(5) pkix(7) id-mod(0)
           id-mod-kemAlgorithmInformation-2023(109) }
   ;


   --
   -- Object Identifiers
   --

   --
   -- Information Object Classes
   --

   pk-CompositeKEM {OBJECT IDENTIFIER:id}
     PUBLIC-KEY ::= {
       IDENTIFIER id
       -- KEY no ASN.1 wrapping --
       PARAMS ARE absent
       CERT-KEY-USAGE { keyEncipherment }
       -- PRIVATE-KEY no ASN.1 wrapping --
     }

   kema-CompositeKEM {
     OBJECT IDENTIFIER:id,
       PUBLIC-KEY:publicKeyType }
       KEM-ALGORITHM ::= {
            IDENTIFIER id
            -- VALUE no ASN.1 wrapping --
            PARAMS ARE absent
            PUBLIC-KEYS { publicKeyType }
            SMIME-CAPS { IDENTIFIED BY id }
           }



   --
   -- Composite KEM Algorithms
   --


   -- Composite ML-KEM
```

```
   id-MLKEM768-RSA2048-SHA3-256 OBJECT IDENTIFIER ::= {
      iso(1) identified-organization(3) dod(6) internet(1) security(5)
      mechanisms(5) pkix(7) alg(6) 55 }

   pk-MLKEM768-RSA2048-SHA3-256 PUBLIC-KEY ::=
     pk-CompositeKEM {
       id-MLKEM768-RSA2048-SHA3-256 }

   kema-MLKEM768-RSA2048-SHA3-256 KEM-ALGORITHM ::=
       kema-CompositeKEM{
         id-MLKEM768-RSA2048-SHA3-256,
         pk-MLKEM768-RSA2048-SHA3-256 }


   id-MLKEM768-RSA3072-SHA3-256 OBJECT IDENTIFIER ::= {
      iso(1) identified-organization(3) dod(6) internet(1) security(5)
      mechanisms(5) pkix(7) alg(6) 56 }

   pk-MLKEM768-RSA3072-SHA3-256 PUBLIC-KEY ::=
     pk-CompositeKEM {
       id-MLKEM768-RSA3072-SHA3-256 }

   kema-MLKEM768-RSA3072-SHA3-256 KEM-ALGORITHM ::=
       kema-CompositeKEM{
         id-MLKEM768-RSA3072-SHA3-256,
         pk-MLKEM768-RSA3072-SHA3-256 }


   id-MLKEM768-RSA4096-SHA3-256 OBJECT IDENTIFIER ::= {
      iso(1) identified-organization(3) dod(6) internet(1) security(5)
      mechanisms(5) pkix(7) alg(6) 57 }


   pk-MLKEM768-RSA4096-SHA3-256 PUBLIC-KEY ::=
     pk-CompositeKEM {
       id-MLKEM768-RSA4096-SHA3-256 }

   kema-MLKEM768-RSA4096-SHA3-256 KEM-ALGORITHM ::=
       kema-CompositeKEM{
         id-MLKEM768-RSA4096-SHA3-256,
         pk-MLKEM768-RSA4096-SHA3-256 }



   id-MLKEM768-X25519-SHA3-256 OBJECT IDENTIFIER ::= {
      iso(1) identified-organization(3) dod(6) internet(1) security(5)
      mechanisms(5) pkix(7) alg(6) 58 }
```

```
pk-MLKEM768-X25519-SHA3-256 PUBLIC-KEY ::=
  pk-CompositeKEM {
    id-MLKEM768-X25519-SHA3-256 }

kema-MLKEM768-X25519-SHA3-256 KEM-ALGORITHM ::=
    kema-CompositeKEM{
      id-MLKEM768-X25519-SHA3-256,
      pk-MLKEM768-X25519-SHA3-256 }


id-MLKEM768-ECDH-P256-SHA3-256 OBJECT IDENTIFIER ::= {
   iso(1) identified-organization(3) dod(6) internet(1) security(5)
   mechanisms(5) pkix(7) alg(6) 59 }


pk-MLKEM768-ECDH-P256-SHA3-256 PUBLIC-KEY ::=
  pk-CompositeKEM {
    id-MLKEM768-ECDH-P256-SHA3-256 }

kema-MLKEM768-ECDH-P256-SHA3-256 KEM-ALGORITHM ::=
    kema-CompositeKEM{
      id-MLKEM768-ECDH-P256-SHA3-256,
      pk-MLKEM768-ECDH-P256-SHA3-256 }


id-MLKEM768-ECDH-P384-SHA3-256 OBJECT IDENTIFIER ::= {
   iso(1) identified-organization(3) dod(6) internet(1) security(5)
   mechanisms(5) pkix(7) alg(6) 60 }


pk-MLKEM768-ECDH-P384-SHA3-256 PUBLIC-KEY ::=
  pk-CompositeKEM {
    id-MLKEM768-ECDH-P384-SHA3-256 }

kema-MLKEM768-ECDH-P384-SHA3-256 KEM-ALGORITHM ::=
    kema-CompositeKEM{
      id-MLKEM768-ECDH-P384-SHA3-256,
      pk-MLKEM768-ECDH-P384-SHA3-256 }


id-MLKEM768-ECDH-brainpoolP256r1-SHA3-256 OBJECT IDENTIFIER ::= {
   iso(1) identified-organization(3) dod(6) internet(1) security(5)
   mechanisms(5) pkix(7) alg(6) 61 }


pk-MLKEM768-ECDH-brainpoolP256r1-SHA3-256 PUBLIC-KEY ::=
  pk-CompositeKEM {
    id-MLKEM768-ECDH-brainpoolP256r1-SHA3-256 }
```

```
   kema-MLKEM768-ECDH-brainpoolP256r1-SHA3-256 KEM-ALGORITHM ::=
       kema-CompositeKEM{
         id-MLKEM768-ECDH-brainpoolP256r1-SHA3-256,
         pk-MLKEM768-ECDH-brainpoolP256r1-SHA3-256 }


   id-MLKEM1024-RSA3072-SHA3-256 OBJECT IDENTIFIER ::= {
      iso(1) identified-organization(3) dod(6) internet(1) security(5)
      mechanisms(5) pkix(7) alg(6) 62 }


   pk-MLKEM1024-RSA3072-SHA3-256 PUBLIC-KEY ::=
     pk-CompositeKEM {
       id-MLKEM1024-RSA3072-SHA3-256 }

   kema-MLKEM1024-RSA3072-SHA3-256 KEM-ALGORITHM ::=
       kema-CompositeKEM{
         id-MLKEM1024-RSA3072-SHA3-256,
         pk-MLKEM1024-RSA3072-SHA3-256 }


   id-MLKEM1024-ECDH-P384-SHA3-256 OBJECT IDENTIFIER ::= {
      iso(1) identified-organization(3) dod(6) internet(1) security(5)
      mechanisms(5) pkix(7) alg(6) 63 }


   pk-MLKEM1024-ECDH-P384-SHA3-256 PUBLIC-KEY ::=
     pk-CompositeKEM {
       id-MLKEM1024-ECDH-P384-SHA3-256 }

   kema-MLKEM1024-ECDH-P384-SHA3-256 KEM-ALGORITHM ::=
       kema-CompositeKEM{
         id-MLKEM1024-ECDH-P384-SHA3-256,
         pk-MLKEM1024-ECDH-P384-SHA3-256 }


   id-MLKEM1024-ECDH-brainpoolP384r1-SHA3-256 OBJECT IDENTIFIER ::= {
      iso(1) identified-organization(3) dod(6) internet(1) security(5)
      mechanisms(5) pkix(7) alg(6) 64 }


   pk-MLKEM1024-ECDH-brainpoolP384r1-SHA3-256 PUBLIC-KEY ::=
     pk-CompositeKEM{
       id-MLKEM1024-ECDH-brainpoolP384r1-SHA3-256 }

   kema-MLKEM1024-ECDH-brainpoolP384r1-SHA3-256 KEM-ALGORITHM ::=
       kema-CompositeKEM{
         id-MLKEM1024-ECDH-brainpoolP384r1-SHA3-256,
```

```
         pk-MLKEM1024-ECDH-brainpoolP384r1-SHA3-256 }


   id-MLKEM1024-X448-SHA3-256 OBJECT IDENTIFIER ::= {
      iso(1) identified-organization(3) dod(6) internet(1) security(5)
      mechanisms(5) pkix(7) alg(6) 65 }


   pk-MLKEM1024-X448-SHA3-256 PUBLIC-KEY ::=
     pk-CompositeKEM {
       id-MLKEM1024-X448-SHA3-256 }

   kema-MLKEM1024-X448 KEM-ALGORITHM ::=
       kema-CompositeKEM{
         id-MLKEM1024-X448-SHA3-256,
         pk-MLKEM1024-X448-SHA3-256 }


   id-MLKEM1024-ECDH-P521-SHA3-256 OBJECT IDENTIFIER ::= {
      iso(1) identified-organization(3) dod(6) internet(1) security(5)
      mechanisms(5) pkix(7) alg(6) 66 }


   pk-MLKEM1024-ECDH-P521-SHA3-256 PUBLIC-KEY ::=
     pk-CompositeKEM {
       id-MLKEM1024-ECDH-P521-SHA3-256 }

   kema-MLKEM1024-ECDH-P521-SHA3-256 KEM-ALGORITHM ::=
       kema-CompositeKEM{
         id-MLKEM1024-ECDH-P521-SHA3-256,
         pk-MLKEM1024-ECDH-P521-SHA3-256 }

   END

   <CODE ENDS>
```

8. IANA Considerations

8.1. Object Identifier Allocations

IANA has registered the Object Identifiers in the "SMI Security for PKIX Algorithms" registry.

8.1.1. Module Registration

The following is to be registered in "SMI Security for PKIX Module Identifier":

* Decimal: IANA Assigned - *Replace TBDMOD*

* Description: Composite-MLKEM-2025 - id-mod-composite-mlkem-2025

* References: This Document

8.1.2. Object Identifier Registrations

The following are registered in the "SMI Security for PKIX Algorithms":

* id-MLKEM768-RSA2048-SHA3-256

  - Decimal: 1.3.6.1.5.5.7.6.55

  - Description: id-MLKEM768-RSA2048-SHA3-256

  - References: This Document

* id-MLKEM768-RSA3072-SHA3-256

  - Decimal: 1.3.6.1.5.5.7.6.56

  - Description: id-MLKEM768-RSA3072-SHA3-256

  - References: This Document

* id-MLKEM768-RSA4096-SHA3-256

  - Decimal: 1.3.6.1.5.5.7.6.57

  - Description: id-MLKEM768-RSA4096-SHA3-256

  - References: This Document

* id-MLKEM768-X25519-SHA3-256

  - Decimal: 1.3.6.1.5.5.7.6.58

  - Description: id-MLKEM768-X25519-SHA3-256

  - References: This Document

* id-MLKEM768-ECDH-P256-SHA3-256

  - Decimal: 1.3.6.1.5.5.7.6.59

  - Description: id-MLKEM768-ECDH-P256-SHA3-256

- References: This Document

* id-MLKEM768-ECDH-P384-SHA3-256

  - Decimal: 1.3.6.1.5.5.7.6.60

  - Description: id-MLKEM768-ECDH-P384-SHA3-256

  - References: This Document

* id-MLKEM768-ECDH-brainpoolP256r1-SHA3-256

  - Decimal: 1.3.6.1.5.5.7.6.61

  - Description: id-MLKEM768-ECDH-brainpoolP256r1-SHA3-256

  - References: This Document

* id-MLKEM1024-RSA3072-SHA3-256

  - Decimal: 1.3.6.1.5.5.7.6.62

  - Description: id-MLKEM1024-RSA3072-SHA3-256

  - References: This Document

* id-MLKEM1024-ECDH-P384-SHA3-256

  - Decimal: 1.3.6.1.5.5.7.6.63

  - Description: id-MLKEM1024-ECDH-P384-SHA3-256

  - References: This Document

* id-MLKEM1024-ECDH-brainpoolP384r1-SHA3-256

  - Decimal: 1.3.6.1.5.5.7.6.64

  - Description: id-MLKEM1024-ECDH-brainpoolP384r1-SHA3-256

  - References: This Document

* id-MLKEM1024-X448-SHA3-256

  - Decimal: 1.3.6.1.5.5.7.6.65

  - Description: id-MLKEM1024-X448-SHA3-256

- References: This Document

* id-MLKEM1024-ECDH-P521-SHA3-256

  - Decimal: 1.3.6.1.5.5.7.6.66

  - Description: id-MLKEM1024-ECDH-P521-SHA3-256

  - References: This Document

9. Security Considerations

As this specification uses ML-KEM as a component of all composite algorithms, all security considerations from [I-D.ietf-lamps-kyber-certificates] and [I-D.sfluhrer-cfrg-ml-kem-security-considerations] apply. Note in particular the "Encapsulation key check" in section 7.2 of [FIPS.203] and the "Decapsulation input check" in section 7.3 of [FIPS.203] which are required for correct and secure functioning of ML-KEM, but which are considered to be external to the Encaps() and Decaps() algorithms.

9.1. Why Hybrids?

In broad terms, a PQ/T Hybrid can be used either to provide dual-algorithm security or to provide migration flexibility. Let's quickly explore both.

Dual-algorithm security. The general idea is that the data is protected by two algorithms such that an attacker would need to break both in order to compromise the data. As with most of cryptography, this property is easy to state in general terms, but becomes more complicated when expressed in formalisms. The following sections go into more detail here.

Migration flexibility. Some PQ/T hybrids exist to provide a sort of "OR" mode where the application can choose to use one algorithm or the other or both. The intention is that the PQ/T hybrid mechanism builds in application backwards compatibility to allow legacy and upgraded applications to co-exist and communicate. The composite algorithms presented in this specification do not provide this since they operate in a strict "AND" mode. They do, however, provide codebase migration flexibility. Consider that an organization has today a mature, validated, certified, hardened implementation of RSA or ECC; composites allow them to add an ML-KEM implementation which immediately starts providing benefits against harvest-now-decrypt-later attacks even if that ML-KEM implementation is still an experimental, non-validated, non-certified, non-hardened implementation. More details of obtaining FIPS certification of a composite algorithm can be found in Section 10.1.

9.2. KEM Combiner

The KEM combiner from Section 3.4 is reproduced here for reference.

```
SHA3-256(mlkemSS || tradSS || tradCT || tradPK || Label)
```

Figure 3: KEM combiner construction

The primary security property of the KEM combiner is that it preserves indistinguishable (adaptive) chosen-ciphertext (IND-CCA2) security of the overall Composite ML-KEM so long as at least one component is IND-CCA2 [X-Wing] [GHP18]. Additionally, we also need to consider the case where one of the component algorithms is completely broken; that the private key is known to an attacker. In this case, we rely on the construction of the KEM combiner to ensure that the value of the other shared secret key cannot be leaked or the combined shared secret key predicted via manipulation of the broken algorithm.

Each registered Composite ML-KEM algorithm specifies a Label -- see Section 6. Given that each Composite ML-KEM algorithm fully specifies the component algorithms, including for example the size of the RSA modulus, all inputs to the KEM combiner are fixed-size and thus do not require length-prefixing.

* mlkemSS is always 32 bytes.

* tradSS in the case of DH this is derived by the decapsulator and therefore the length is not controlled by the attacker, however in the case of RSA-OAEP this value is directly chosen by the sender and both the length and content could be freely chosen by an attacker.

* tradCT is either an elliptic curve public key or an RSA-OAEP ciphertext which is required to have its length checked by step 1b of RSAES-OAEP-DECRYPT in [RFC8017].

* tradPK is the public key of the traditional component (elliptic curve or RSA) and therefore fixed-length.

* Label is a fixed value specified in this document.

9.2.1. IND-CCA2 Security of the hybrid scheme

Informally, a Composite ML-KEM algorithm is secure if the combiner (SHA3) is secure, and either ML-KEM is secure or the traditional component (RSA-OAEP, ECDH, X25519 or X448) is secure.

The security of ML-KEM and DH hybrids is covered in [X-Wing] and requires that the first KEM component (ML-KEM in this construction) is IND-CCA2 and second ciphertext preimage resistant (C2PRI) and that the DH component is nominal group; i.e. a well-behaved elliptic curve DH group, but does not require the traditional component to be IND-CCA. This design choice improves performance by not including the large ML-KEM public key and ciphertext, but means that an implementation error in the ML-KEM component that affects the ciphertext check step of the FO transform could result in the overall composite no longer achieving IND-CCA2 security. This solution remains IND-CCA2 due to binding the tradPK and tradCT in the KEM combiner.

The QSF framework presented in [X-Wing] is extended to cover RSA-OAEP as the traditional algorithm in place of DH. Informally we note that that RSA-OAEP is IND-CCA2 secure [RFC8017] but is not C2PRI(aka ciphertext binding) or public key binding since it is mathematically possibly to construct two RSA-OAEP ciphertexts that decapsulate to the same shared secret under the same public key or under different public keys. Binding the RSA-OAEP ciphertext and public key to the internal KDF restores these properties. Formally, [Starhunters] ports the proof of [X-Wing] to cover RSA-OAEP as the traditional compenent in a QSF construction. [KWW2026] goes further, analyzing a range of different RSA-based KEMs, including the RSA-OAEP-KEM construction used in this specification, concluding that it achieves LEAK-BIND-K,PK-CT and C2PRI when the ciphertext is included in the post-processing KDF.

The composite combiner cannot be assumed to be secure when used with different KEMs and a more cautious approach would bind the public key and ciphertext of the first KEM as well.

9.2.2. Second pre-image resistance of component KEMs

The notion of a "ciphertext second pre-image resistant KEM" is defined in [X-Wing] as being the property that it is computationally difficult to find two different ciphertexts c != c' that will decapsulate to the same shared secret key under the same public key. For the purposes of a hybrid KEM combiner, this property means that given two composite ciphertexts (c1, c2) and (c1', c2'), we must obtain a unique overall shared secret key so long as either c1 != c1' or c2 != c2' -- i.e. the overall Composite ML-KEM is ciphertext second pre-image resistant, and therefore secure so long as one of the component KEMs is secure.

In [X-Wing] it is proven that ML-KEM is a second pre-image resistant KEM and therefore the ML-KEM ciphertext can safely be omitted from the KEM combiner. Note that this makes a fundamental assumption on ML-KEM remaining ciphertext second pre-image resistant, and therefore this formulation of KEM combiner does not fully protect against implementation errors in the ML-KEM component -- particularly around the ciphertext check step of the Fujisaki-Okamoto transform -- which could trivially lead to second ciphertext pre-image attacks that break the IND-CCA2 security of the ML-KEM component and of the overall Composite ML-KEM. This could be more fully mitigated by binding the ML-KEM ciphertext in the combiner, but a design decision was made to settle for protection against algorithmic attacks and not implementation attacks against ML-KEM in order to increase performance.

However, since neither RSA-OAEP nor DH guarantee second pre-image resistance at all, even in a correct implementation, these ciphertexts are bound to the key derivation in order to guarantee that c != c' will yield a unique ciphertext, and thus restoring second pre-image resistance to the overall Composite ML-KEM.

9.2.3. Generifying this construction

It should be clear that the security analysis of the presented KEM combiner construction relies heavily on the specific choices of component algorithms and combiner KDF, and this combiner construction SHOULD NOT by applied to any other combination of ciphers without performing the appropriate security analysis.

9.3. Key Reuse

While conformance with this specification requires that both components of a composite key MUST be freshly generated, the designers are aware that some implementers may be forced to break this rule due to operational constraints. This section documents the implications of doing so.

When using single-algorithm cryptography, the best practice is to always generate fresh keying material for each purpose, for example when renewing a certificate, or obtaining both a TLS and S/MIME certificate for the same device. However, in practice key reuse in such scenarios is not always catastrophic to security and therefore often tolerated. However this reasoning does not hold in the PQ/T hybrid setting.

Within the broader context of PQ/T hybrids, we need to consider new attack surfaces that arise due to the hybrid constructions and did not exist in single-algorithm contexts. One of these is key reuse where the component keys within a hybrid are also used by themselves within a single-algorithm context. For example, it might be tempting for an operator to take already-deployed RSA keys and add an ML-KEM key to them to form a hybrid. Within a hybrid signature context this leads to a class of attacks referred to as "stripping attacks" where one component signature can be extracted and presented as a single-algorithm signature. Hybrid KEMs using a concatenation-style KEM combiner, as is done in this specification, do not have the analogous attack surface because even if an attacker is able to extract and decrypt one of the component ciphertexts, this will yield a different shared secret key than the overall shared secret key derived from the composite, so any subsequent symmetric cryptographic operations will fail.

In addition, there is a further implication to key reuse regarding certificate revocation. Upon receiving a new certificate enrolment request, many certification authorities will check if the requested public key has been previously revoked due to key compromise. Often a CA will perform this check by using the public key hash. Therefore, if one, or even both, components of a composite have been previously revoked, the CA may only check the hash of the combined composite key and not find the revocations. Therefore, because the possibility of key reuse exists even though forbidden in this specification, CAs performing revocation checks on a composite key SHOULD also check both component keys independently to verify that the component keys have not been revoked.

9.4. Policy for Deprecated and Acceptable Algorithms

Traditionally, a public key or certificate contains a single cryptographic algorithm. If and when an algorithm becomes deprecated (for example, RSA-512, or SHA1), the path to deprecating it through policy and removing it from operational environments is, at least is principle, straightforward.

In the composite model this is less obvious since a PQ/T hybrid is expected to still be considered valid after the traditional component is deprecated for individual use. As such, a single composite public key or certificate may contain a mixture of deprecated and non-deprecated algorithms. In general this should be manageable through policy by removing OIDs for the standalone component algorithms while still allowing OIDs for composite algorithms. However, complications may arise when the composite implementation needs to invoke the cryptographic module for a deprecated component algorithm. In particular, this could lead to complex Cryptographic Bills of Materials that show implementations of deprecated algorithms still present and being used.

10. Implementation Considerations

10.1. FIPS Certification

The following sections give guidance to implementers wishing to FIPS-certify a composite implementation.

This guidance is not authoritative and has not been endorsed by NIST.

Implementers seeking FIPS certification of a composite KEM algorithm where only one of the component algorithms has been FIPS-validated or FIPS-approved should credit the FIPS-validated component algorithm with full security strength, the non-FIPS-validated component algorithm with zero security, and the overall composite should be considered at least as strong and thus FIPS-approved.

The composite algorithm has been designed to treat the underlying primitives as "black-box implementations" and not impose any additional requirements on them that could require an existing implementation of an underlying primitive to run in a mode different from the one under which it was certified. For example, the KeyGen defined in Section 3.1 invokes ML-KEM.KeyGen_internal(d, z) which might not be available in a cryptographic module running in FIPS-mode, but Section 3.1 is only a suggested implementation and the composite KeyGen MAY be implemented using a different available interface for ML-KEM.KeyGen.

The authors wish to note that composite algorithms provide a design pattern to provide utility in future situations that require care to remain FIPS-compliant, such as future cryptographic migrations as well as bridging across jurisdictions with non-intersecting cryptographic requirements.

Successful FIPS certification will need to take into account the "Encapsulation key check" in section 7.2 of [FIPS.203] and the "Decapsulation input check" in section 7.3 of [FIPS.203] which are required for correct and secure functioning of ML-KEM, but which are considered to be external to the Encaps() and Decaps() algorithms.

The following sections go into further detail on specific issues that relate to FIPS certification.

10.1.1. Combiner Function

For reference, the KEM combiner used in Composite ML-KEM is:

```
ss = SHA3-256(mlkemSS || tradSS || tradCT || tradPK || Label)
```

NIST SP 800-227 [SP800-227] allows hybrid key combiners of the following form:

```
K <- KDM((S1,S2,...,St), OtherInput)           (14)
```

Composite ML-KEM maps cleanly into this since it places the two shared secret keys mlkemSS || tradSS at the beginning of the KDF input such that all other inputs tradCT || tradPK || Label can be considered part of OtherInput for the purposes of FIPS certification.

For the detailed steps of the Key Derivation Mechanism KDM, [SP800-227] refers to [SP.800-56Cr2].

Compliance of the Composite ML-KEM variants is achieved in the following way:

The Composite ML-KEM algorithms use SHA3, and so can be certified under [SP.800-56Cr2] One-Step Key Derivation Option 1: H(x) = hash(x).

[SP.800-56Cr2] section 4 "One-Step Key Derivation" requires a counter which begins at the 4-byte value 0x00000001. However, the counter is allowed to be omitted when the hash function is executed only once, as specified on page 159 of the FIPS 140-3 Implementation Guidance [FIPS-140-3-IG].

10.1.2. Order of KDF inputs with Non-Approved Algorithms

[SP800-227] adds an important stipulation that was not present in earlier NIST specifications:

> This publication approves the use of the key combiner (14) for any t > 1, so long as at least one shared secret (i.e., S_j for some j) is a shared secret generated from the key- establishment methods of SP 800-56A or SP 800-56B, or an approved KEM.

This means that although Composite ML-KEM always places the shared secret key from ML-KEM in the first slot, a Composite ML-KEM can be FIPS certified so long as either component is FIPS certified. This is important for several reasons. First, in the early stages of PQC migration, composites allow for a non-FIPS certified ML-KEM implementation to be added to a module that already has a FIPS certified traditional component, and the resulting composite can be FIPS certified. Second, when eventually RSA and Elliptic Curve are no longer FIPS-allowed, the composite can retain its FIPS certified status on the strength of the ML-KEM component. Third, while this is outside the scope of this specification, the general composite construction could be used to create FIPS certified algorithms that contain a component algorithm from a different jurisdiction. Third, a composite where both components are FIPS-certified could allow an implementer to patch one component algorithm while awaiting re-certification while continuing to use the overall composite in FIPS mode.

Note that before [SP800-227] was in force, [SP.800-56Cr2] required the shared secret key from the certified algorithm to be in the first slot and therefore a Composite ML-KEM implementation using a FIPS-certified traditional component and a non-FIPS certified ML-KEM is not believed to be certifiable under [SP.800-56Cr2] alone, and requires the ammendments made by [SP800-227].

10.2. Backwards Compatibility

The term "application backwards compatibility" is used here to mean that existing systems as they are deployed today can interoperate with the upgraded systems of the future. This draft explicitly does not provide application backwards compatibility, only upgraded systems will understand the OIDs defined in this specification.

These migration and interoperability concerns need to be thought about in the context of various types of protocols that make use of X.509 and PKIX with relation to key establishment and content encryption, from online negotiated protocols such as TLS 1.3 [RFC8446] and IKEv2 [RFC7296], to non-negotiated asynchronous protocols such as S/MIME signed email [RFC8551], as well as myriad other standardized and proprietary protocols and applications that leverage CMS [RFC5652] encrypted structures.

10.3. Profiling down the number of options

One daunting aspect of this specification is the number of composite algorithm combinations. Each option has been specified because there is a community that has a direct application for it; typically because the traditional component is already deployed in a change-managed environment, or because that specific traditional component is required for regulatory reasons.

However, this large number of combinations leads either to fracturing of the ecosystem into non-interoperable sub-groups when different communities choose non-overlapping subsets to support, or on the other hand it leads to spreading development resources too thin when trying to support all options.

This specification does not list any particular composite algorithm as mandatory-to-implement, however organizations that operate within specific application domains are encouraged to define profiles that select a small number of composites appropriate for that application domain. For applications that do not have any regulatory requirements or legacy implementations to consider, it is RECOMMENDED to focus implementation effort on:

id-MLKEM768-X25519-SHA3-256 (aka "X-Wing")
id-MLKEM768-ECDH-P256-SHA3-256

In applications that only allow NIST PQC Level 5, it is RECOMMENDED to focus implementation effort on:

id-MLKEM1024-ECDH-P384-SHA3-256

10.4. Decapsulation Requires the Public Key

ML-KEM always requires the public key in order to perform various steps of the Fujisaki-Okamoto decapsulation [FIPS.203], and for this reason the private key encoding specified in FIPS 203 includes the public key.

Moreover, the KEM combiner as specified in Section 3.4 requires the public key of the traditional component in order to achieve the public-key binding property and ciphertext collision resistance as described in Section 9.2. Since tradPK is not carried in the composite private key encoding, the implementation is required to obtain it from some out-of-band mechanism. This section discusses several options, but is a non-normative, non-exhaustive list.

1. Derive or extract from private key. Many cryptographic modules expose functionality to obtain an RSA or EC public key from the corresponding private key. For applications where such functionality does not exist, Section 10.4.1 and Section 10.4.2 provide the suggested mechanisms for extracting the public keys from private keys for RSA and ECDH respectively. It is assumed that this is not required for X25519 or X448 since those private keys are seeds from which the public key can be obtained.

2. Fetch it from an external data source, for example from the public-key certificate corresponding to this private key.

3. If the composite KEM private key is being carried within a PKCS#8 OneAsymmetricKey object, place the full composite public key within the optional OneAsymmetricKey.publicKey field, which allows extracting the tradPK (and re-encode as necessary for correctly using it in the KEM Combiner).

4. Use an alternate private key encoding that explicitly carries the tradPK.

10.4.1. Extracting RSAPublicKey from RSAPrivateKey

Assuming that the RSA component of the composite private key is encoded as an RSAPrivateKey, as required by this specification, then, quoting from [RFC8017] you have:

```
RSAPrivateKey ::= SEQUENCE {
    version           Version,
    modulus           INTEGER,  -- n
    publicExponent    INTEGER,  -- e
    privateExponent   INTEGER,  -- d
    prime1            INTEGER,  -- p
    prime2            INTEGER,  -- q
    exponent1         INTEGER,  -- d mod (p-1)
    exponent2         INTEGER,  -- d mod (q-1)
    coefficient       INTEGER,  -- (inverse of q) mod p
    otherPrimeInfos   OtherPrimeInfos OPTIONAL
}
```

This can trivially be converted into an RSAPublicKey through simple DER decoding / re-encoding since both required values are already present.

```
RSAPublicKey ::= SEQUENCE {
    modulus           INTEGER,  -- n
    publicExponent    INTEGER   -- e
}
```

10.4.2. Deriving the public ECPoint from ECPrivateKey

Unlike RSA, the ECPrivateKey does not contain sufficient information to simply extract the public key. Note that in the interest of having a single unique encoding to foster interoperability, this specification forbids the optional publicKey field.

That said, the EC public key can be derived from the private key in the following way:

```
g = generator for the group P256r1, P384r1, etc.
s = ECPrivateKey.getS()

pubKey = ec_multiply_by_scalar(g, s)
```

where a recommended implementation of ec_multiply_by_scalar() can be found in [SEC1].

Then encode pubKey as X9.62 uncompressed point.

11. References

11.1. Normative References

[FIPS.202] National Institute of Standards and Technology (NIST), "SHA-3 Standard: Permutation-Based Hash and Extendable-Output Functions", August 2015, <https://nvlpubs.nist.gov/nistpubs/FIPS/NIST.FIPS.202.pdf>.

[FIPS.203] National Institute of Standards and Technology (NIST), "Module-Lattice-based Key-Encapsulation Mechanism Standard", August 2024, <https://nvlpubs.nist.gov/nistpubs/FIPS/NIST.FIPS.203.pdf>.

[FIPS.204] National Institute of Standards and Technology (NIST), "Module-Lattice-Based Digital Signature Standard", August 2024, <https://nvlpubs.nist.gov/nistpubs/FIPS/NIST.FIPS.204.pdf>.

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Appendix A. Maximum Key and Ciphertext Sizes

The sizes listed below are maximum values: several factors could cause fluctuations in the size of the traditional component. For example, this could be due to:

* The RSA public key (n, e) allows e to vary in size between 3 and n - 1 [RFC8017]. Note that the size table below assumes the recommended value of e = 65537, so for RSA combinations it is in fact not a true maximum.

* When the underlying RSA or EC value is itself DER-encoded, integer values could occasionally be shorter than expected due to leading zeros being dropped from the encoding.

By contrast, ML-KEM values are always fixed size, so composite values can always be correctly de-serialized based on the size of the ML-KEM component.

Size values marked with an asterisk (*) in the table are not fixed but maximum possible values for the composite key or ciphertext. Implementations MUST NOT perform strict length checking based on such values.

Non-hybrid ML-KEM is included for reference.

Algorithm	Public key	Private key	Ciphertext	SS
id-alg-ml-kem-768	1184	64	1088	32
id-alg-ml-kem-1024	1568	64	1568	32
id-MLKEM768-RSA2048-SHA3-256	1454*	1258*	1344	32
id-MLKEM768-RSA3072-SHA3-256	1582*	1834*	1472	32
id-MLKEM768-RSA4096-SHA3-256	1710*	2415*	1600	32
id-MLKEM768-X25519-SHA3-256	1216	96	1120	32
id-MLKEM768-ECDH-P256-SHA3-256	1249	115	1153	32
id-MLKEM768-ECDH-P384-SHA3-256	1281	128	1185	32
id-MLKEM768-ECDH-brainpoolP256r1-SHA3-256	1249	116	1153	32
id-MLKEM1024-RSA3072-SHA3-256	1966*	1834*	1952	32
id-MLKEM1024-ECDH-P384-SHA3-256	1665	128	1665	32
id-MLKEM1024-ECDH-brainpoolP384r1-SHA3-256	1665	132	1665	32
id-MLKEM1024-X448-SHA3-256	1624	120	1624	32
id-MLKEM1024-ECDH-P521-SHA3-256	1701	146	1701	32

Table 3: Maximum size values of composite ML-KEM

Appendix B. Component Algorithm Reference

This section provides references to the full specification of the algorithms used in the composite constructions.

Component KEM Algorithm ID	OID	Specification
id-ML-KEM-768	2.16.840.1.101.3.4.4.2	[FIPS.203]
id-ML-KEM-1024	2.16.840.1.101.3.4.4.3	[FIPS.203]
id-X25519	1.3.101.110	[RFC7748], [RFC8410]
id-X448	1.3.101.111	[RFC7748], [RFC8410]
id-ecDH	1.3.132.1.12	[RFC5480], [RFC5915], [SEC1]
id-RSAES-OAEP	1.2.840.113549.1.1.7	[RFC8017]

Table 4: Component Encryption Algorithms used in Composite Constructions

Elliptic CurveID	OID	Specification
secp256r1	1.2.840.10045.3.1.7	[RFC6090], [SEC2]
secp384r1	1.3.132.0.34	[RFC6090], [SEC2]
secp521r1	1.3.132.0.35	[RFC6090], [SEC2]
brainpoolP256r1	1.3.36.3.3.2.8.1.1.7	[RFC5639]
brainpoolP384r1	1.3.36.3.3.2.8.1.1.11	[RFC5639]

Table 5: Elliptic Curves used in Composite Constructions

HashID	OID	Specification
id-sha3-256	2.16.840.1.101.3.4.2.8	[FIPS.202]

Table 6: Hash algorithms used in Composite Constructions

Appendix C. Fixed Component Algorithm Identifiers

Many cryptographic libraries are X.509-focused and do not expose interfaces to instantiate a public key from raw bytes, but only from a SubjectPublicKeyInfo structure as you would find in an X.509 certificate, therefore implementing Composite ML-KEM in those libraries requires reconstructing the SPKI for each component algorithm. In order to aid implementers and reduce interoperability issues, this section lists out the full public key for each component algorithm.

ML-KEM-768

ASN.1:

```
algorithm AlgorithmIdentifier ::= {
  algorithm id-alg-ml-kem-768   -- (2.16.840.1.101.3.4.4.2)
  }
```

DER:

```
30 0B 06 07 60 86 48 01 65 03 04 04 02
```

ML-KEM-1024

ASN.1:

ASN.1:

```
algorithm AlgorithmIdentifier ::= {
  algorithm id-alg-ml-kem-1024   -- (2.16.840.1.101.3.4.4.3)
  }
```

DER:

```
30 0B 06 07 60 86 48 01 65 03 04 04 03
```

RSA-OAEP - all sizes

```
 ASN.1:
   algorithm AlgorithmIdentifier ::= {
     algorithm id-RSAES-OAEP,   -- (1.2.840.113549.1.1.7)
     parameters RSAES-OAEP-params {
          hashFunc      [0] id-sha256,  -- (2.16.840.1.101.3.4.2.1)
          maskGenFunc   [1] mgf1SHA256Identifier,
          pSourceFunc   [2] pSpecifiedEmpty  }
     }


 where
       mgf1SHA256Identifier  AlgorithmIdentifier  ::=  {
                             algorithm id-mgf1,  -- (1.2.840.113549.1.1.8)
                             parameters sha256Identifier }


       sha256Identifier  AlgorithmIdentifier  ::=  { id-sha256, NULL }

 DER:
  30 4D 06 09 2A 86 48 86 F7 0D 01 01 07 30 40 A0 0F 30 0D 06 09 60 86
  48 01 65 03 04 02 01 05 00 A1 1C 30 1A 06 09 2A 86 48 86 F7 0D 01 01
  08 30 0D 06 09 60 86 48 01 65 03 04 02 01 05 00 A2 0F 30 0D 06 09 2A
  86 48 86 F7 0D 01 01 09 04 00
```

ECDH NIST-P-256

```
   ASN.1:
     algorithm AlgorithmIdentifier ::= {
       algorithm id-ecPublicKey   -- (1.2.840.10045.2.1)
       parameters ANY ::= {
         AlgorithmIdentifier ::= {
           algorithm secp256r1    -- (1.2.840.10045.3.1.7)
           }
         }
       }

   DER:
     30 13 06 07 2A 86 48 CE 3D 02 01 06 08 2A 86 48 CE 3D 03 01 07
```

ECDH NIST-P-384

ASN.1:

```
algorithm AlgorithmIdentifier ::= {
  algorithm id-ecPublicKey   -- (1.2.840.10045.2.1)
  parameters ANY ::= {
    AlgorithmIdentifier ::= {
      algorithm secp384r1    -- (1.3.132.0.34)
      }
    }
  }
```

DER:

```
30 10 06 07 2A 86 48 CE 3D 02 01 06 05 2B 81 04 00 22
```

ECDH NIST-P-521

ASN.1:

```
algorithm AlgorithmIdentifier ::= {
  algorithm id-ecPublicKey   -- (1.2.840.10045.2.1)
  parameters ANY ::= {
    AlgorithmIdentifier ::= {
      algorithm secp521r1    -- (1.3.132.0.35)
      }
    }
  }
```

DER:

```
30 10 06 07 2A 86 48 CE 3D 02 01 06 05 2B 81 04 00 23
```

ECDH Brainpool-256

ASN.1:

```
algorithm AlgorithmIdentifier ::= {
  algorithm id-ecPublicKey   -- (1.2.840.10045.2.1)
  parameters ANY ::= {
    AlgorithmIdentifier ::= {
      algorithm brainpoolP256r1   -- (1.3.36.3.3.2.8.1.1.7)
      }
    }
  }
```

DER:

```
30 14 06 07 2A 86 48 CE 3D 02 01 06 09 2B 24 03 03 02 08 01 01 07
```

ECDH Brainpool-384

ASN.1:

```
algorithm AlgorithmIdentifier ::= {
  algorithm id-ecPublicKey   -- (1.2.840.10045.2.1)
  parameters ANY ::= {
    AlgorithmIdentifier ::= {
      algorithm brainpoolP384r1   -- (1.3.36.3.3.2.8.1.1.11)
      }
    }
  }
```

DER:

```
30 14 06 07 2A 86 48 CE 3D 02 01 06 09 2B 24 03 03 02 08 01 01 0B
```

X25519

ASN.1:

```
algorithm AlgorithmIdentifier ::= {
  algorithm id-X25519   -- (1.3.101.110)
  }
```

DER:

```
30 05 06 03 2B 65 6E
```

X448

ASN.1:

```
algorithm AlgorithmIdentifier ::= {
  algorithm id-X448   -- (1.3.101.111)
  }
```

DER:

```
30 05 06 03 2B 65 6F
```

Appendix D. Comparison with other Hybrid KEMs

D.1. X-Wing

This specification borrows extensively from the analysis and KEM combiner construction presented in [X-Wing]. In particular, X-Wing and id-MLKEM768-X25519-SHA3-256 are largely interchangeable. The one difference is that X-Wing uses a combined KeyGen function to generate the two component private keys from the same seed, which gives some additional binding properties. In order to allow for re-use of existing hardeneded certified cryptographic modules (for example, getting the RSA component from an existing smartcard), this specification keeps the key generation for both components separate and only loosely-specified so that implementers are free to use an existing certified hardware or software module for one or both components.

D.2. ETSI CatKDF

[ETSI.TS.103.744] section 8.2.3 defines CatKDF as:

1) Form secret = psk || k1 || k2.
2) Set context = f(info, MA, MB), where f is a context formatting function.
3) key_material = KDF(secret, label, context, length).
4) Return key_material.

MA shall contain all of the public keys.
MB shall contain all of the corresponding public keys and ciphertexts.

The main difference between the Composite ML-KEM combiner and the ETSI CatKDF combiner is that CatKDF makes the more conservative choice to bind the public keys and ciphertexts of both components, while Composite ML-KEM follows the analysis presented in [X-Wing] that while preserving the security properties of the traditional component requires binding the public key and ciphertext of the traditional component, it is not necessary to do so for ML-KEM thanks to the rejection sampling step of the Fujisaki-Okamoto transform.

Additionally, ETSI CatKDF can be instantiated with either HMAC [RFC2104], KMAC [SP.800-185] or HKDF [RFC5869] as KDF. Since this specification uses SHA3-256 as the KDF for all variants, there is no equivalent construction of CatKDF.

Appendix E. Examples of KEM Combiner Intermediate Values

This section provides examples of constructing the input for the KEM Combiner, showing all intermediate values. This is intended to be useful for debugging purposes. See Section 3.4 for additional information.

Each input component is shown. Note that values are shown hex-encoded for display purposes only, they are actually raw binary values.

* mlkemSS is the shared secret produced by the ML-KEM encapsulate or decapsulate function which is always 32 bytes.

* tradSS is the shared secret produce by the traditional algorithm.

* tradCT is either an elliptic curve public key or an RSA-OAEP ciphertext depending on the algorithm chosen.

* tradPK is the public key of the traditional component (elliptic curve or RSA) and therefore fixed-length.

* Label is the specific KEM Combiner Label for this composite algorithm. See Section 6

Next, the Combined KDF Input is given, which is simply the concatenation of the above values.

Finally, the KDF Function and the ss Output are shown as outputs. The ss is the Composite ML-KEM shared-secret generated by applying the KDF to the Combined KDF Input.

Examples are given for each recommended Composite ML-KEM algorithm from Section 10.3.

Example 1:

Example of id-MLKEM768-ECDH-P256-SHA3-256 Combiner function output.

```
# Inputs
mlkemSS:
ca48920ded22e063f98a79a4091508678b7042cab63f78c571ff392e82612d43

tradSS:
ef1c92443aaf987000e3470d34332b4c53ff0cdd4554b6bf377bf7bdb677d3d0

tradCT:  041d155f6d3078d7e2cd4f9f758947029795dd9ab6d6e92d81d1917127
0cdefcd4abb682edbb22faf961ce75fc688109931bfa24468f646b97eca4d57d5f5
e7610

tradPK:  04ba2bfbf7b91182eb1fad54a2940c8b1dfd53de55fa3c02d199a3159f
f73d38d29aa94f32e3e82bcc99b165320297149455997d7c3ea5ac97cd987d3e803
96a3e

Label:  4d4c4b454d3736382d50323536

        (ascii: "MLKEM768-P256")


# Combined KDF Input:
#  mlkemSS || tradSS || tradCT || tradPK || Label

Combined KDF Input: ca48920ded22e063f98a79a4091508678b7042cab63f78c
571ff392e82612d43ef1c92443aaf987000e3470d34332b4c53ff0cdd4554b6bf37
7bf7bdb677d3d0041d155f6d3078d7e2cd4f9f758947029795dd9ab6d6e92d81d19
171270cdefcd4abb682edbb22faf961ce75fc688109931bfa24468f646b97eca4d5
7d5f5e761004ba2bfbf7b91182eb1fad54a2940c8b1dfd53de55fa3c02d199a3159
ff73d38d29aa94f32e3e82bcc99b165320297149455997d7c3ea5ac97cd987d3e80
396a3e4d4c4b454d3736382d50323536


# Outputs
# ss = SHA3-256(Combined KDF Input)

ss:
d6c69aa6e986b620a2777d8cf1fb6be1b2255d6efae0566deb34c882b38846ee
```

Example 2:

```
Example of id-MLKEM768-X25519-SHA3-256 Combiner function output.

# Inputs
mlkemSS:
461b74b074818906edcd2fd976008caca5247f496670ae86e34abe35e62a7ae1

tradSS:
4c62bd6d6f76294f3c14d7e79dbf56e4bf82cb1fb803accfaf2a59c1663a8843

tradCT:
0ec7210a4aa22bb75af9243f95a6ccf857e872efbe5e77e8e917b56178fa473f

tradPK:
1e9d4f72d56cef589864e102c6d6fa86cd3ac5163839556f7555ad083f37b03b

Label:  5c2e2f2f5e5c

        (ascii: "\.//^\")


# Combined KDF Input:
#  mlkemSS || tradSS || tradCT || tradPK || Label

Combined KDF Input: 461b74b074818906edcd2fd976008caca5247f496670ae8
6e34abe35e62a7ae14c62bd6d6f76294f3c14d7e79dbf56e4bf82cb1fb803accfaf
2a59c1663a88430ec7210a4aa22bb75af9243f95a6ccf857e872efbe5e77e8e917b
56178fa473f1e9d4f72d56cef589864e102c6d6fa86cd3ac5163839556f7555ad08
3f37b03b5c2e2f2f5e5c


# Outputs
# ss = SHA3-256(Combined KDF Input)

ss:
21ee673fdeac21dd78ef13bc8432a50c0ac31893cbe97d14c0e82f5fe4a28d98

Example 3:
```

Example of id-MLKEM1024-ECDH-P384-SHA3-256 Combiner function output.

```
# Inputs
mlkemSS:
c0f87f0c53fa8e2ba192a494694d37d1e3cf99c65e0dc5f69b2cc044b3fb205d

tradSS:  4d52b7ef430382f479603207c0b8f7aa5bc35d8758835007e39a2642ad
65e635d674db7a5513889657fb24e4e228a098

tradCT:  0401a5b81dcb51290a0eb142b9032d5a37503164b7a20ac0e3b52dc54f
9b0b7c9fdd2699a59563a0b9ad0e54478846faeab72b92275e1fbb8b963bcc6e80e
30c089fbe4ed8d47ec76951db94aede46e679d5692eeb1d1b150d5b2e6660dc67c4
69

tradPK:  0468cc4acc5dd85edbcbf25bae7ee7dcacec2968ea7ee57fc91311cb9c
47d4a24c3854e5ce3e5d0b309fda493224520f2870496eb16571108b3deafd72c1d
f17edc302fbb8b60bae44d93177e6df5278e4667a090a2d59a2076f41d693975e8d
19

Label:  4d4c4b454d313032342d50333834

        (ascii: "MLKEM1024-P384")


# Combined KDF Input:
#  mlkemSS || tradSS || tradCT || tradPK || Label

Combined KDF Input: c0f87f0c53fa8e2ba192a494694d37d1e3cf99c65e0dc5f
69b2cc044b3fb205d4d52b7ef430382f479603207c0b8f7aa5bc35d8758835007e3
9a2642ad65e635d674db7a5513889657fb24e4e228a0980401a5b81dcb51290a0eb
142b9032d5a37503164b7a20ac0e3b52dc54f9b0b7c9fdd2699a59563a0b9ad0e54
478846faeab72b92275e1fbb8b963bcc6e80e30c089fbe4ed8d47ec76951db94aed
e46e679d5692eeb1d1b150d5b2e6660dc67c4690468cc4acc5dd85edbcbf25bae7e
e7dcacec2968ea7ee57fc91311cb9c47d4a24c3854e5ce3e5d0b309fda493224520
f2870496eb16571108b3deafd72c1df17edc302fbb8b60bae44d93177e6df5278e4
667a090a2d59a2076f41d693975e8d194d4c4b454d313032342d50333834


# Outputs
# ss = SHA3-256(Combined KDF Input)

ss:
eb60f6c80a309ad4158d7b02f2cf8c947faead96ebbd85c3f62a94868ffddca4
```

Appendix F. Test Vectors

The following test vectors are provided in a format similar to the NIST ACVP Known-Answer-Tests (KATs).

The structure is that a global cacert is provided which is used to sign each KEM certificate.

Within each test case there are the following values:

* tcId the name of the algorithm.
* ek the encapsulation public key.
* x5c the X.509 certificate of the encapsulation key, signed by the cacert.
* dk the raw decapsulation private key.
* dk_pkcs8 the decapsulation private key in a PKCS#8 object.
* c the ciphertext.
* k the derived shared secret key.

Implementers should be able to perform the following tests using the test vectors below:

1. Load the public key ek or certificate x5c and perform an encapsulation for it (you should obtain valid ct and k values, but they will not match the ones in the test vector since Encap() is randomized.)
2. Load the decapsulation private key dk or dk_pkcs8 and the ciphertext c and perform a Decaps() operation to ensure that the same shared secret key k is derived.

Test vectors are provided for each underlying ML-KEM algorithm in isolation for the purposes of debugging.

Due to the length of the test vectors, some readers will prefer to retrieve the non-word-wrapped copy from GitHub [TestVectors]. The reference implementation written in python that generated them is also available.


```
{
"cacert": "MIIVpzCCCKSgAwIBAgIUPGsGMD62FcFQ7UWtEng5AYgngTkwCwYJYIZIA
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TENMAsGA1UECgwESUVURjEOMAwGA1UECwwFTEFNUFMxHDAaBgNVBAMME0NvbXBvc2l0Z
SBNTC1LRU0gQ0EwggeyMAsGCWCGSAFlAwQDEgOCB6EABoBhTR3o2qD4gk8GmzyvPQord
rVrFGg8Ri4zNm+vD17WNb5hKwAGMdJy9a7Zehf/mQnbRDHRNSi4xdiyhYKepsLEubVN9
5eMpHRGdIOJie7QbQ7NM6xGq714j+D7UpKpHTeFWNeNwNvQoPpiAKXHrJutAHKD9f/G4
```

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/La79fg6+56aEV6+gUZKQxEZ9885BOoZ6rYMZoGMcIUPvWntVHxwtmB3q1hn3WWT7SuP
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Appendix G. Contributors and Acknowledgments

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