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D. Connolly
SandboxAQ
P. Schwabe
MPI-SP & Radboud University
B. E. Westerbaan
Cloudflare
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X-Wing: general-purpose hybrid post-quantum KEM
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Abstract

This memo defines X-Wing, a general-purpose post-quantum/traditional hybrid key encapsulation mechanism (PQ/T KEM) built on X25519 and ML-KEM-768.

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://dconnolly.github.io/draft-connolly-cfrg-xwing-kem/draft-connolly-cfrg-xwing-kem.html>. Status information for this document may be found at <https://datatracker.ietf.org/doc/draft-connolly-cfrg-xwing-kem/>.

Discussion of this document takes place on the Crypto Forum Research Group mailing list (<mailto:cfrg@ietf.org>), which is archived at https://mailarchive.ietf.org/arch/search/?email_list=cfrg. Subscribe at <https://www.ietf.org/mailman/listinfo/cfrg/>.

Source for this draft and an issue tracker can be found at <https://github.com/dconnolly/draft-connolly-cfrg-xwing-kem>.

Status of This Memo

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1. Introduction

1.1. Motivation

There are many choices that can be made when specifying a hybrid KEM: the constituent KEMs; their security levels; the combiner; and the hash within, to name but a few. Having too many similar options are a burden to the ecosystem.

The aim of X-Wing is to provide a concrete, simple choice for post-quantum hybrid KEM, that should be suitable for the vast majority of use cases.

1.2. Design goals

By making concrete choices, we can simplify and improve many aspects of X-Wing.

- * Simplicity of definition. Because all shared secrets and cipher texts are fixed length, we do not need to encode the length. Using SHA3-256, we do not need HMAC-based construction. For the concrete choice of ML-KEM-768, we do not need to mix in its ciphertext, see Section 6.

- * Security analysis. Because ML-KEM-768 already assumes the Quantum Random Oracle Model (QROM), we do not need to complicate the analysis of X-Wing by considering stronger models.
- * Performance. Not having to mix in the ML-KEM-768 ciphertext is a nice performance benefit. Furthermore, by using SHA3-256 in the combiner, which matches the hashing in ML-KEM-768, this hash can be computed in one go on platforms where two-way Keccak is available.

We aim for "128 bits" security (NIST PQC level 1). Although at the moment there is no peer-reviewed evidence that ML-KEM-512 does not reach this level, we would like to hedge against future cryptanalytic improvements, and feel ML-KEM-768 provides a comfortable margin.

We aim for X-Wing to be usable for most applications, including specifically HPKE [RFC9180].

1.3. Not an interactive key-agreement

Traditionally most protocols use a Diffie-Hellman (DH) style non-interactive key-agreement. In many cases, a DH key agreement can be replaced by the interactive key-agreement afforded by a KEM without change in the protocol flow. One notable example is TLS [HYBRID] [XYBERTLS]. However, not all uses of DH can be replaced in a straight-forward manner by a plain KEM.

1.4. Not an authenticated KEM

In particular, X-Wing is not, borrowing the language of [RFC9180], an `_authenticated_` KEM.

1.5. Comparisons

1.5.1. With HPKE X25519Kyber768Draft00

X-Wing is most similar to HPKE's X25519Kyber768Draft00 [XYBERHPKE]. The key differences are:

- * X-Wing uses the final version of ML-KEM-768.
- * X-Wing hashes the shared secrets, to be usable outside of HPKE.
- * X-Wing has a simpler combiner by flattening DHKEM(X25519) into the final hash.
- * X-Wing does not hash in the ML-KEM-768 ciphertext.

There is also a different KEM called X25519Kyber768Draft00 [XYBERTLS] which is used in TLS. This one should not be used outside of TLS, as it assumes the presence of the TLS transcript to ensure non malleability.

1.5.2. With generic combiner

The generic combiner of [I-D.ounsworth-cfrg-kem-combiners] can be instantiated with ML-KEM-768 and DHKEM(X25519). That achieves similar security, but:

- * X-Wing is more performant, not hashing in the ML-KEM-768 ciphertext, and flattening the DHKEM construction, with the same level of security.
- * X-Wing has a fixed 32 byte shared secret, instead of a variable shared secret.
- * X-Wing does not accept the optional counter and fixedInfo arguments.

2. Requirements Notation

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.

3. Conventions and Definitions

This document is consistent with all terminology defined in [I-D.driscoll-pqt-hybrid-terminology].

The following terms are used throughout this document to describe these operations:

- * `concat(x0, ..., xN)`: returns the concatenation of byte strings.
`concat(0x01, 0x0203, 0x040506) = 0x010203040506.`
- * `random(n)`: returns a byte string of length `n` bytes produced by a cryptographically-secure pseudorandom number generator.

4. Cryptographic Dependencies

X-Wing relies on the following primitives:

- * ML-KEM-768 post-quantum key-encapsulation mechanism (KEM) [MLKEM]:

- ML-KEM-768.KeyGen_internal(d, z): Deterministic algorithm to generate an ML-KEM-768 key pair (pk_M, sk_M) of an encapsulation key pk_M and decapsulation key sk_M. It is the derandomized version of ML-KEM-768.KeyGen. Note that ML-KEM-768.KeyGen_internal() returns the keys in reverse order of GenerateKeyPair() defined below. d and z are both 32 byte strings.
- ML-KEM-768.Encaps(pk_M): Randomized algorithm to generate (ss_M, ct_M), an ephemeral 32 byte shared key ss_M, and a fixed-length encapsulation (ciphertext) of that key ct_M for encapsulation key pk_M.

ML-KEM-768.Encaps(pk_M) MUST perform the encapsulation key check of [MLKEM] 則 7.2 and raise an error if it fails.

- ML-KEM-768.Decap(ct_M, sk_M): Deterministic algorithm using the decapsulation key sk_M to recover the shared key from ct_M.

ML-KEM-768.Decap(ct_M, sk_M) is NOT required to perform the decapsulation key check of [MLKEM] 則 7.3.

To generate deterministic test vectors, we also use

- ML-KEM-768.Encaps_internal(pk_M, m): Algorithm to generate (ss_M, ct_M), an ephemeral 32 byte shared key ss_M, and a fixed-length encapsulation (ciphertext) of that key ct_M for encapsulation key pk_M. m is a 32 byte string.

ML-KEM-768.Encaps_internal(pk_M) MUST perform the encapsulation key check of [MLKEM] 則 7.2 and raise an error if it fails.

- * X25519 elliptic curve Diffie-Hellman key-exchange defined in Section 5 of [RFC7748]:

- X25519(k, u): takes 32 byte strings k and u representing a Curve25519 scalar and the u-coordinate of a point respectively, and returns the 32 byte string representing the u-coordinate of their scalar multiplication.
- X25519_BASE: the 32 bytestring representing the standard base point of Curve25519. In hexadecimal, it is given by 0900.

Note that 9 is the standard basepoint for X25519, cf Section 6.1 of [RFC7748].

- * Symmetric cryptography.

- SHAKE256(message, outlen): The extendable-output function (XOF) with that name defined in Section 6.2 of [FIPS202]. Note that outlen counts bits.
- SHA3-256(message): The hash with that name defined in Section 6.1 of [FIPS202].

5. X-Wing Construction

5.1. Encoding and sizes

X-Wing encapsulation key, decapsulation key, ciphertexts and shared secrets are all fixed-length byte strings.

Decapsulation key (private): 32 bytes

Encapsulation key (public): 1216 bytes

Ciphertext: 1120 bytes

Shared secret: 32 bytes

5.2. Key generation

An X-Wing keypair (decapsulation key, encapsulation key) is generated as follows.

```
def expandDecapsulationKey(sk):
    expanded = SHAKE256(sk, 96*8) # expand sk to 96 bytes using SHAKE256
    (pk_M, sk_M) = ML-KEM-768.KeyGen_internal(expanded[0:32], expanded[32:64])
    sk_X = expanded[64:96]
    pk_X = X25519(sk_X, X25519_BASE)
    return (sk_M, sk_X, pk_M, pk_X)
```

```
def GenerateKeyPair():
    sk = random(32)
    (sk_M, sk_X, pk_M, pk_X) = expandDecapsulationKey(sk)
    return sk, concat(pk_M, pk_X)
```

GenerateKeyPair() returns the 32 byte secret decapsulation key sk and the 1216 byte encapsulation key pk.

Here and in the balance of the document for clarity we use the M and X subscripts for ML-KEM-768 and X25519 components respectively.

5.2.1. Key derivation

For testing, it is convenient to have a deterministic version of key generation. An X-Wing implementation MAY provide the following derandomized variant of key generation.

```
def GenerateKeyPairDerand(sk):
    sk_M, sk_X, pk_M, pk_X = expandDecapsulationKey(sk)
    return sk, concat(pk_M, pk_X)
```

sk must be 32 bytes.

GenerateKeyPairDerand() returns the 32 byte secret encapsulation key sk and the 1216 byte decapsulation key pk.

Note GenerateKeyPair() is the same as GenerateKeyPairDerand(random(32)).

5.3. Combiner

Given 32 byte strings ss_M, ss_X, ct_X, pk_X, representing the ML-KEM-768 shared secret, X25519 shared secret, X25519 ciphertext (ephemeral public key) and X25519 public key respectively, the 32 byte combined shared secret is given by:

```
def Combiner(ss_M, ss_X, ct_X, pk_X):
    return SHA3-256(concat(
        ss_M,
        ss_X,
        ct_X,
        pk_X,
        XWingLabel
    ))
```

where XWingLabel is the following 6 byte ASCII string

```
XWingLabel = concat(
    "\./",
    "/^\",
)
```

In hexadecimal, XWingLabel is given by 5c2e2f2f5e5c.

5.4. Encapsulation

Given an X-Wing encapsulation key pk, encapsulation proceeds as follows.

```
def Encapsulate(pk):
    pk_M = pk[0:1184]
    pk_X = pk[1184:1216]
    ek_X = random(32)
    ct_X = X25519(ek_X, X25519_BASE)
    ss_X = X25519(ek_X, pk_X)
    (ss_M, ct_M) = ML-KEM-768.Encaps(pk_M)
    ss = Combiner(ss_M, ss_X, ct_X, pk_X)
    ct = concat(ct_M, ct_X)
    return (ss, ct)
```

pk is a 1216 byte X-Wing encapsulation key resulting from
GeneratePublicKey()

Encapsulate() returns the 32 byte shared secret ss and the 1120 byte
ciphertext ct.

Note that Encapsulate() may raise an error if the ML-KEM
encapsulation does not pass the check of [MLKEM] 則 7.2.

5.4.1. Derandomized

For testing, it is convenient to have a deterministic version of
encapsulation. An X-Wing implementation MAY provide the following
derandomized function.

```
def EncapsulateDerand(pk, eseed):
    pk_M = pk[0:1184]
    pk_X = pk[1184:1216]
    ek_X = eseed[32:64]
    ct_X = X25519(ek_X, X25519_BASE)
    ss_X = X25519(ek_X, pk_X)
    (ss_M, ct_M) = ML-KEM-768.EncapsDerand(pk_M, eseed[0:32])
    ss = Combiner(ss_M, ss_X, ct_X, pk_X)
    ct = concat(ct_M, ct_X)
    return (ss, ct)
```

pk is a 1216 byte X-Wing encapsulation key resulting from
GeneratePublicKey() eseed MUST be 64 bytes.

EncapsulateDerand() returns the 32 byte shared secret ss and the 1120
byte ciphertext ct.

Encapsulate(pk) can be implemented as
EncapsulateDerand(pk, random(64)).

5.5. Decapsulation

```
def Decapsulate(ct, sk):
    (sk_M, sk_X, pk_M, pk_X) = expandDecapsulationKey(sk)
    ct_M = ct[0:1088]
    ct_X = ct[1088:1120]
    ss_M = ML-KEM-768.Decapsulate(ct_M, sk_M)
    ss_X = X25519(sk_X, ct_X)
    return Combiner(ss_M, ss_X, ct_X, pk_X)
```

ct is the 1120 byte ciphertext resulting from Encapsulate() sk is a 32 byte X-Wing decapsulation key resulting from GenerateKeyPair()

Decapsulate() returns the 32 byte shared secret.

5.5.1. Keeping expanded decapsulation key around

For efficiency, an implementation MAY cache the result of expandDecapsulationKey. This is useful in two cases:

1. If multiple ciphertexts for the same key are decapsulated.
2. If a ciphertext is decapsulated for a key that has just been generated. This happens on the client-side for TLS.

A typical API pattern to achieve this optimization is to have an opaque decapsulation key object that hides the cached values. For instance, such an API could have the following functions.

1. GenerateKeyPair() returns an encapsulation key and an opaque object that contains the expanded decapsulation key.
2. Decapsulate(ct, esk) takes a ciphertext and an expanded decapsulation key.
3. PackDecapsulationKey(sk) takes an expanded decapsulation key, and returns the packed decapsulation key.
4. UnpackDecapsulationKey(sk) takes a packed decapsulation key, and returns the expanded decapsulation key. In the case of X-Wing this would be the same as a derandomized GenerateKeyPair().

The expanded decapsulation key could cache even more computation, such as the expanded matrix A in ML-KEM.

Any such expanded decapsulation key MUST NOT be transmitted between implementations, as this could break the security analysis of X-Wing. In particular, the MAL-BIND-K-PK and MAL-BIND-K-CT binding properties of X-Wing do not hold when transmitting the regular ML-KEM decapsulation key.

5.6. Use in HPKE

X-Wing satisfies the HPKE KEM interface as follows.

The `SerializePublicKey`, `SerializePrivateKey`, and `DeserializePrivateKey` are the identity functions, as X-Wing keys are fixed-length byte strings, see Section 5.1.

`DeriveKeyPair()` is given by

```
def DeriveKeyPair(ikm):  
    # Extract 32-byte seed from variable-length ikm using SHAKE.  
    sk = SHAKE256(ikm, 32*8)  
    return GenerateKeyPairDerand(sk)
```

where the HPKE private key and public key are the X-Wing decapsulation key and encapsulation key respectively.

`Encap()` is `Encapsulate()` from Section 5.4, where an ML-KEM encapsulation key check failure causes an HPKE `EncapError`.

`Decap()` is `Decapsulate()` from Section 5.5.

X-Wing is not an authenticated KEM: it does not support `AuthEncap()` and `AuthDecap()`, see Section 1.4.

`Nsecret`, `Nenc`, `Npk`, and `Nsk` are defined in Section 7.

5.7. Use in TLS 1.3

For the client's share, the `key_exchange` value contains the X-Wing encapsulation key.

For the server's share, the `key_exchange` value contains the X-Wing ciphertext.

On ML-KEM encapsulation key check failure, the server MUST abort with an `illegal_parameter` alert.

5.8. Use in X.509 Public Key Infrastructure

We use the OID 1.3.6.1.4.1.62253.25722 to identify X-Wing keys as described below. In ASN.1 notation:

```
id-XWing OBJECT IDENTIFIER ::= { iso(1) identified-organization(3)  
    dod(6) internet(1) private(4) enterprise(1) 62253 25722 }
```

5.8.1. Certificate

In a X.509 certificate, the `subjectPublicKeyInfo` field has the `SubjectPublicKeyInfo` type, which has the following ASN.1 syntax.

```
SubjectPublicKeyInfo ::= SEQUENCE {
    algorithm      AlgorithmIdentifier,
    subjectPublicKey BIT STRING
}

AlgorithmIdentifier{ALGORITHM-TYPE, ALGORITHM-TYPE:AlgorithmSet} ::=
SEQUENCE {
    algorithm      ALGORITHM-TYPE."&"id({AlgorithmSet}),
    parameters     ALGORITHM-TYPE.
                    "&"Params({AlgorithmSet}{@algorithm}) OPTIONAL
}
```

An X-Wing encapsulation key **MUST** be encoded directly using the ASN.1 type `XWingPublicKey`.

```
XWingPublicKey ::= OCTET STRING
```

The X-Wing encapsulation key is mapped to a `subjectPublicKey` (a value of type `BIT STRING`) as follows: the most significant bit of the `OCTET STRING` value becomes the most significant bit of the `BIT STRING` value, and so on; the least significant bit of the `OCTET STRING` becomes the least significant bit of the `BIT STRING`.

The `id-XWing` identifier **MUST** be used as the `algorithm` field in the `SubjectPublicKeyInfo` to identify an X-Wing encapsulation key.

The contents of the `parameters` component **MUST** be absent.

5.8.2. Private key

Below we replicate part of the definition of `OneAsymmetricKey` from [RFC5958].

```

OneAsymmetricKey ::= SEQUENCE {
    version                Version,
    privateKeyAlgorithm    SEQUENCE {
        algorithm          PUBLIC-KEY.&id({PublicKeySet}),
        parameters        PUBLIC-KEY.&Params({PublicKeySet}
                                {@privateKeyAlgorithm.algorithm})
                                OPTIONAL}
    privateKey             OCTET STRING (CONTAINING
        PUBLIC-KEY.&PrivateKey({PublicKeySet}
                                {@privateKeyAlgorithm.algorithm})),
    attributes             [0] Attributes OPTIONAL,
    ...
    [[2: publicKey        [1] BIT STRING (CONTAINING
        PUBLIC-KEY.&Params({PublicKeySet}
                                {@privateKeyAlgorithm.algorithm})
                                OPTIONAL,
    ...
}

```

When storing an X-Wing decapsulation key in a `OneAsymmetricKey`, the `privateKey` OCTET STRING contains the raw octet string encoding the X-Wing decapsulation key.

The `id-XWing` identifier MUST be used as the algorithm field in the `OneAsymmetricKey` to identify an X-Wing decapsulation key.

The `publicKey` component MUST be absent.

6. Security Considerations

Informally, X-Wing is secure if SHA3 is secure, and either X25519 is secure, or ML-KEM-768 is secure.

More precisely, if SHA3-256, SHA3-512, and SHAKE-256 may be modelled as a random oracle, then the IND-CCA security of X-Wing is bounded by the IND-CCA security of ML-KEM-768, and the gap-CDH security of Curve25519, see [PROOF].

The security of X-Wing relies crucially on the specifics of the Fujisaki-Okamoto transformation used in ML-KEM-768: the X-Wing combiner cannot be assumed to be secure, when used with different KEMs. In particular it is not known to be safe to leave out the post-quantum ciphertext from the combiner in the general case.

6.1. Binding properties

Some protocols rely on further properties of the KEM. X-Wing satisfies the binding properties MAL-BIND-K-PK and MAL-BIND-K-CT (TODO: reference to proof). This implies [KSMW] X-Wing also satisfies

- * MAL-BIND-K,CT-PK
- * MAL-BIND-K,PK-CT
- * LEAK-BIND-K-PK
- * LEAK-BIND-K-CT
- * LEAK-BIND-K,CT-PK
- * LEAK-BIND-K,PK-CT
- * HON-BIND-K-PK
- * HON-BIND-K-CT
- * HON-BIND-K,CT-PK
- * HON-BIND-K,PK-CT

In contrast, ML-KEM on its own does not achieve MAL-BIND-K-PK, MAL-BIND-K-CT, nor MAL-BIND-K,PK-CT. [SCHMIEG]

7. IANA Considerations

This document requests/registers a new entry to the "HPKE KEM Identifiers" registry.

Value: 25722 = 25519 + 203 = 0x647a (please)

KEM: X-Wing

Nsecret: 32

Nenc: 1120

Npk: 1216

Nsk: 32

Auth: no

Reference: This document

Furthermore, this document requests/registers a new entry to the TLS Named Group (or Supported Group) registry, according to the procedures in Section 6 of [TLSIANA].

Value: 25722 = 25519 + 203 = 0x647a (please)

Description: X-Wing

DTLS-OK: Y

Recommended: N

Reference: This document

Comment: PQ/T hybrid of X25519 and ML-KEM-768

Finally, for the ASN.1 module in {asn1}, IANA is requested to assign an object identifier (OID) for the module identifier (TBD) with a Description of "id-mod-XWing-kem-2024".

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Appendix A. Implementations

- * Platform
 - Apple CryptoKit (<https://developer.apple.com/documentation/cryptokit/xwingmlkem768x25519>)
- * C
 - Google's BoringSSL (<https://github.com/google/boringssl/blob/main/include/openssl/xwing.h>)
- * Go
 - Cloudflare's CIRCL (<https://github.com/cloudflare/circl/pull/471>)
 - Filippo (<https://github.com/FiloSottile/mlkem768>)
- * Rust
 - xwing-kem.rs (<https://github.com/rugo/xwing-kem.rs>)

Note: implements the older -00 version of this memo at the time of writing.

- RustCrypto x-wing
(<https://github.com/RustCrypto/KEMs/tree/master/x-wing>)
- Orion (<https://github.com/orion-rs/orion>)

Appendix B. Machine-readable specification

For the convenience of implementors, we provide a reference specification in Python. This is a specification; not production ready code: it should not be deployed as-is, as it leaks the private key by its runtime.

B.1. xwing.py

```
# WARNING This is a specification of X-Wing; not a production-ready
# implementation. It is slow and does not run in constant time.

# Requires the CryptoDome for SHAKE, and pytest for testing. To install, run
#
# pip install pycryptodome pytest

import binascii
import hashlib

import mlkem
import x25519

XWingLabel = br"""
    \./
    /^\
    """.replace(b'\n', b'').replace(b' ', b'')

assert len(XWingLabel) == 6
assert binascii.hexlify(XWingLabel) == b'5c2e2f2f5e5c'

def expandDecapsulationKey(seed):
    expanded = hashlib.shake_256(seed).digest(length=96)
    pkM, skM = mlkem.KeyGen(expanded[0:64], mlkem.params768)
    skX = expanded[64:96]
    pkX = x25519.X(skX, x25519.BASE)
    return skM, skX, pkM, pkX

def GenerateKeyPairDerand(seed):
    assert len(seed) == 32
    skM, skX, pkM, pkX = expandDecapsulationKey(seed)
```

```

    return seed, pkM + pkX

def Combiner(ssM, ssX, ctX, pkX):
    return hashlib.sha3_256(
        ssM +
        ssX +
        ctX +
        pkX +
        XWingLabel
    ).digest()

def EncapsulateDerand(pk, eseed):
    assert len(eseed) == 64
    assert len(pk) == 1216
    pkM = pk[0:1184]
    pkX = pk[1184:1216]
    ekX = eseed[32:64]
    ctX = x25519.X(ekX, x25519.BASE)
    ssX = x25519.X(ekX, pkX)
    ctM, ssM = mlkem.Enc(pkM, eseed[0:32], mlkem.params768)
    ss = Combiner(ssM, ssX, ctX, pkX)
    return ss, ctM + ctX

def Decapsulate(ct, sk):
    assert len(ct) == 1120
    assert len(sk) == 32
    ctM = ct[0:1088]
    ctX = ct[1088:1120]
    skM, skX, pkM, pkX = expandDecapsulationKey(sk)
    ssM = mlkem.Dec(skM, ctM, mlkem.params768)
    ssX = x25519.X(skX, ctX)
    return Combiner(ssM, ssX, ctX, pkX)

```

B.2. x25519.py

```

# WARNING This is a specification of X25519; not a production-ready
# implementation. It is slow and does not run in constant time.

```

```

p = 2**255 - 19
a24 = 121665

BASE = b'\x09' + b'\x00'*31

def decode(bs):
    return sum(bs[i] << 8*i for i in range(32)) % p

def decodeScalar(k):
    bs = list(k)

```

```
    bs[0] &= 248
    bs[31] &= 127
    bs[31] |= 64
    return decode(bs)

# See rfc7748 §5.
def X(k, u):
    assert len(k) == 32
    assert len(u) == 32

    k = decodeScalar(k)
    u = decode(u)
    x1, x2, x3, z2, z3, swap = u, 1, u, 0, 1, 0

    for t in range(255, -1, -1):
        kt = (k >> t) & 1
        swap ^= kt
        if swap == 1:
            x3, x2 = x2, x3
            z3, z2 = z2, z3
            swap = kt

        A = x2 + z2
        AA = (A*A) % p
        B = x2 - z2
        BB = (B*B) % p
        E = AA - BB
        C = x3 + z3
        D = x3 - z3
        DA = (D*A) % p
        CB = (C*B) % p
        x3 = DA + CB
        x3 = (x3 * x3) % p
        z3 = DA - CB
        z3 = (x1 * z3 * z3) % p
        x2 = (AA * BB) % p
        z2 = (E * (AA + (a24 * E) % p)) % p

    if swap == 1:
        x3, x2 = x2, x3
        z2, z3 = z3, z2

    ret = (x2 * pow(z2, p-2, p)) % p
    return bytes((ret >> 8*i) & 255 for i in range(32))
```

B.3. mlkem.py

draft-schwabe-cfrg-kyber/kyber.py

Appendix C. Test vectors # TODO: replace with test vectors that re-use
ML-KEM, X25519 values

```
seed      7f9c2ba4e88f827d616045507605853ed73b8093f6efbc88eb1a6eacfa66ef26
sk        7f9c2ba4e88f827d616045507605853ed73b8093f6efbc88eb1a6eacfa66ef26
pk
e2236b35a8c24b39b10aa1323a96a919a2ced88400633a7b07131713fc14b2b5b19cfc3d
a5fala92c49f25513e0fd30d6b1611c9ab9635d7086727a4b7d21d34244e66969cf15b3b
2a785329f61b096b277ea037383479a6b556de7231fe4b7fa9c9ac24c0699a0018a52534
01bacfa905ca816573e56a2d2e067e9b7287533ba13a937dedb31fa44baced4076992361
0034ae31e619a170245199b3c5c39864859felb4c9717a07c30495bdfb98a0a002ccf56c
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3bfac32c39c30869374c05c1aeb1898b6b303cc68be455346ee0af699636224a148ca2ae
a10463111c709f69b69c70ce8538746698c4c60a9aef0030c7924ceec42a5d36816f545e
ae13293460b3acb37ea0e13d70e4aa78686da398a8397c08eaf96882113fe4f7bad4da40
b0501e1c753efe73053c87014e8661c33099afe8bede414a5blaa27d8392b3e131e9a70c
1055878240cad0f40d5fe3cdf85236ead97e2a97448363b2808caafd516cd25052c5c362
543c2517e4acd0e60ec07163009b6425fc32277acee71c24bab53ed9f29e74c66a0a3564
955998d76b96a9a8b50d1635a4d7a67eb42df5644d330457293a8042f53cc7a69288f17e
d55827e82b28e82665a86a14fbd96645eca8172c044f83bc0d8c0b4c8626985631ca87af
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317714cb4102cb7b2f9a25b2b4f0615de31dec9ca55026d6da0b65111b16fe52feed8a4
87e144462a6dba93728f500b6ffc49e515569ef25fed17aff520507368253525860f58be
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fe90083c91c7a6d43d4fb15f48c60c2fd66e0a8aad4ad64e5c42bb8877c0ebec2b5e387c
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d3bc86151c43aad185712717340223ac381d21150a04294e97bb13bbda21b5a182b6da96
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eff389b27dce59844570216223593d4ba32d9abac8cd049040ef6534
eseed
3cb1eea988004b93103cfb0aeefd2a686e01fa4a58e8a3639ca8a1e3f9ae57e235b8cc87
3c23dc62b8d260169afa2f75ab916a58d974918835d25e6a435085b2
ct
```

b83aa828d4d62b9a83ceffeld3d3bb1ef31264643c070c5798927e41fb07914a273f8f96
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a0c475f63ee6890157c7116dae3f62bf72f60acd2bb8cc31ce2ba0de364f52b8ed38c79d
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2d00e4c790d965d7a03a3c0b4222ba8c2a9a16e2ac658f572ae0e746eafc4feba023576f
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14cafb9c7c0e85fe543d56658c213632599efabfc1ec49dd8c88547bb2cc40c9d38cbd30
99b4547840560531d0188cd1e9c23a0ebee0a03d5577d66b1d2bcb4baaf21cc7fef1e038
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dec71d595bfbbe94b5ed4bc07d800b330796fda89edb77be0294136139354eb8cd3759157
8f9c600dd9be8ec6219fdd507adf3397ed4d68707b8d13b24ce4cd8fb22851bfe9d63240
7f31ed6f7cb1600de56f17576740ce2a32fc5145030145cfb97e63e0e41d354274a079d3
e6fb2e15

ss d2df0522128f09dd8e2c92b1e905c793d8f57a54c3da25861f10bf4ca613e384

seed badfd6dfaacc359a5efbb7bcc4b59d538df9a04302e10c8bc1cbf1a0b3a5120ea

sk badfd6dfaacc359a5efbb7bcc4b59d538df9a04302e10c8bc1cbf1a0b3a5120ea

pk 0333285fa253661508c9fb444852caa4061636cb060e69943b431400134ael1fbc0228724
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f30aca7c09380255a0c621602ffbb6a9db064c1406d12723ab3bbe2950a21fe521b160b3
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eseed
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33c923b4c927e8747c6f830c441a8bd3c5b371f6b3ab8103ebcfb18543aefc1beb6f776b
bfd5344779f4aa23daaf395f69ec31dc046b491f0e5cc9c651dfc306bd8f2105be7bc7a4
f4e21957f87278c771528a8740a92e2daefa76a3525f1fae17ec4362a2700988001d8600
11d6ca3a95f79a0205bcf634cef373a8ea273ff0f4250eb8617d0fb92102a6aa09cf0c3e
e2cad1ad96438c8e4dfd6ee0fcc85833c3103dd6c1600cd305bc2df4cda89b55ca237a3f
9c3f82390074ff30825fc750130ebaf13d0cf7556d2c52a98a4bad39ca5d44aaadeaef77
5c695e64d06e966acfcdd552a14e2df6c63ae541f0fa88fc48263089685704506a21a0385
6ce65d4f06d54f3157eeabd62491cb4ac7bf029e79f9fbd4c77e2a3588790c710e611da8
b2040c76a61507a8020758dcc30894ad018fef98e401cc54106e20d94bd544a8f0elfd05
00342d123f618aa8c91bdf6e0e03200693c9651e469aee6f91c98bea4127ae66312f4ae3
ea155b67
ss f2e86241c64d60f6649fbc6c5b7d17180b780a3f34355e64a85749949c45f150
seed ef58538b8d23f87732ea63b02b4fa0f4873360e2841928cd60dd4cee8cc0d4c9
sk ef58538b8d23f87732ea63b02b4fa0f4873360e2841928cd60dd4cee8cc0d4c9
pk 36244278824f77c621c660892c1c3886a9560caa52a97c461fd3958a598e749bbc8c7798
ac8870bac7318ac2b863000ca3b0bdcbbclccfcb1a30875df9a76976763247083e646ccb
2499a4e4f0c9f4125378ba3da1999538b86f99f2328332c177d1192b849413e655101289
73f679d23253850bb6c347ba7ca81b5e6ac4c574565c731740b3cd8c9756caac39fba7ac
422acc60c6c1a645b94e3b6d21485ebad9c4fe5bb4ea0853670c5246652bfff65ce8381cb
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23ec260f0571e3ec12a9c82d9db3c57b3a99e8701f78db4fabclcc58b1bae02745073a81
fc8045439ba3b885581a283a1ba64e103610aabb4ddfe9959e7241011b2638b56ba6a982
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4ba9b03cf611e70486edf539767c7485189d5f1b08e32a274dc24a39c918fd2a4dfa946a
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alac74b128b148d1b9412aa66948cac6dc6614681fda02ca86675d2a756003c49c50f06e
13c63ce4bc9f321c860b202ee931834930011f485c9af86b9f642f0c353ad305c66996b9
a136b753973929495f0d8048db75529edcb4935904797ac66605490f66329c3bb36b8573
a3e00f817b3082162ff106674d11b261baae0506cde7e69fdce93c6c7b59b9d4c759758a
cf287c2e4c4bfab5170a9236daf21bdb6005e92464ee8863f845cf37978ef19969264a51
6fe992c93b5f7ae7cb6718ac69257d630379e4aac6029cb906f98d91c92d118c36a6d161
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b5a07f78ec0f5c5759e5a4322bca2643425748a1a97c62108510c44fd9089c5a7c14e57b
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2a47418be9cfb582b1dcfa3d9aa45299b79fff265356d8286a1ca2f3c2184b2a70d15289
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29293ab77747d85310078682e0ba0ac236548d905a79494324574d417c7a3457bd5fb525
3c4876679034ae844d0d05010fec722db5621e3a67a2d58e2ff33b432269169b51f9dcc0
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d10931b0daa5a2f2a405017688c991e586b522f94b1132bc7e87a63246475816c8be9c62
b731691ab912eb656ce2619225663364701a014b7d0337212caa2ecc731f34438289e0ca

```
4590a276802d980056b5d0d316cae2ecfea6d86696a9f161aa90ad47eaad8cadd31ae3cb
c1c013747dfee80fb35b5299f555dcc2b787ea4f6f16ffdf66952461
eseed
22a96188d032675c8ac850933c7aff1533b94c834adbb69c6115bad4692d8619f90b0cdf
8a7b9c264029ac185b70b83f2801f2f4b3f70c593ea3aeeb613a7f1b
ct
0d2e38cbf17a2e2e4e0c87a94ca1e7701ae1552e02509b3b00f9c82c39e3fd435b05b912
75f47abc9f1021429a26a346598cd6cd9efdc8adc1dbc35036d0290bf89733c835309202
232f9bf652ea82f3d49280d6e8a3bd3135fb883445ab5b074d949c5350c7c7d6ac59905b
dbf6e6639da8a9d4b390ecc1dd05522d2956f2d37a05593996e5cb3fd8d5a9eb52417732
e1ebf545588713b4760227115aab7ada178dadbc583b26cfedba2888a0c95b950bf07f7
50d7aa8103798aa3470a042c0105c6a037de2f9ebc396021b2ba2c16aba696fbac3454dc
8e053b8fa55edd45215eeb57a1eab9106fb426b375a9b9e5c3419efc7610977e72640f9f
d1b2ec337de33c35e5a7581b2aae4d8ee86d2e0ebf82a1350714de50d2d788687878a196
44ae4e3175e8d59dc90171b3badeff65aeaf600e5e5483a3595fdeb40cbafcb040c29a2
f6900533ae999d24f54dfcef748c30313ca447cdddfa57ad78eaa890e90f3f7bf8d11696
8a5713cc75fd0408f36364fa265c5617039304eaeac4cbee6fc49b9fe2276768cdbec2d7
3a507b543cc028dc1b154b7c2b0412254c466a94a8d6ea3a47e1743469bd45c08f54cf96
5884be3696e961741ede16e3b1bc4feb93faaeef31d911dc0cb3fa90bcda991959a9d2cbc
817a5564c5c01177a59e9577589ea344d60cf5b0aa39f31863febd54603ca87ad2363c76
6642a3f52557bcd9e4c05a87665842ba336b83156a677030f0bad531a8387a1486a599ca
a748fcea7bdclb63f3cdb97173551ab7c1c36b69acbbdb2ff7a1e7bc70439632ddc67b9
7f3dal5f59b3c1588515957cb8a2f86ab635ce0a78b7cdf24eac3445e8fc8b79ba04da9e9
03f49a7d912c197a84b4cfabc779b97d24788419bcf58035db99717edb9fd1c1df8c4005
f700eabba528ddfcbada6dd30754f795948a34c9319ab653524b19931c7900c4167988a
f52292fe902e746b524d20cefffb4339e8f5535f41cf35f0f8ea8b4a7b949c5d2381116b1
46e9b913a83a3fal6c65ff9468c835fe4114554a6c66a80e1c9a6bb064b380be3c95e5595
ec979bf1c85aa938938e3f10e72b0c87811969e8ab0d83de0b0604c4016ac3a015e19514
089271bdc6ebf2ec56fab6018e44de749b4c36cc235e370da8466dbdc253542a2d704eb3
316fd70d5d238cb7eaaf05966d973f62c7ef43b9a806f4ed213ac8099ea15d61a9024441
60883f6bf441a3e1469945c9b79489ea18390f1ebc83caca10bdb8f2429877b52bd44c94
a228ef91c392ef5398c5c83982701318ccedab92f7a279c4fddebba7fe5e986c48b7d813
5b3fe4cd15be2004ce73ff86b1e55f8ecd6ba5b8114315f8e716ef3ab0a64564a4644651
166ebd68b1f783e2e443dbccadfe189368647629f1a12215840b7f1d026de2f665c2eb02
3ff51a6df160912811ee03444ae4227fb941dc9ec4f31b445006fd384de5e60e0a5061b5
0cb1202f863090fc05eb814e2d42a03586c0b56f533847ac7b8184ce9690bc8dece32a88
ca934f541d4cc520fa64de6b6e1c3c8e03db5971a445992227c825590688d203523f5271
61137334
ss      953f7f4e8c5b5049bdc771d1dffada0dd961477d1a2ae0988baa7ea6898d893f
```

Appendix D. Example of use in X.509

The following are the encodings of the X-Wing keypair with private key 0001...1f.

```

-----BEGIN PRIVATE KEY-----
MDQCAQAwDQYLKwYBBAGD5i2ByHoEIAABAgMEBQYHCAkKCwwNDg8QERITFBUWFxgZ
GhsCHR4f
-----END PRIVATE KEY-----

-----BEGIN PUBLIC KEY-----
MIIE1DANBgsrBgEEAYPmLYHIEgOCBMEAb1QJigoOZBFGYUtpYLPg2GA9YvRH+atJ
m0e9aQbMQLBh2GNKPoiQbyhJWODEHKbHJcu5cJW3ZxpGK2aByeZYC7yNYLFI+mAm
EEOvu6UvIFpgKDhIUvLq3zcavqmNM0c4PSu2c0OPZ4NhK/hwFPe5Gol0AmU0XfZ5
NARz0cTBdohuXim48Fi7fHNTFmhs/1w764wmHLAJcKacGvzFS5TLhuHOY7pjbJlc
pFEB4hx70EwxPqGa8kFB79KtREFqJbpPZZEO99iAnDCT8EqvAOPNluNcSqPIAsGK
1vOdpLS42YyL15Atg6B7pFOWZ0pgJDyrk+gP2bHid3N2qcnNb6EV4mOTgLnGvnhI
vRNYjGRwOgU10ZoPgWM6l2oKEftm7ihdD9JV6CwDMZJfQ4O278dh72CZi1oLmHJj
WKqdAbi41lGfkhR0u3wUuyIlK1wvENQSRsmyPnZehJNn9UGhX208koo5u3vHPwe2
ZcSWu2VYyPRUIacuxLrNNOnFlMM4cbcj8DSV6ItDkasm5DBD3rYRezKZ5FxmGxar
KOR93XI2Y4VHZhkvwYBspwq7eGy9swky5oyKNwvPsHmDoBLDJmuT76YmV/S4ODdM
sLuV4OwGVBSHzdmc8V08a5YTXKeApVs2R3ieMZFeRig8+ce7boRT+2aCEFFB8dWN
ANhe7XA7bGyWH3nIRSdrQkiUnAZ4LlE+spkblldlgQuOMvtolJEmytQhOvaUiamIG
QAeJEwowlkSYSLYp/upKLCp0PEon3Jyz89Z2/FY3MbJsShpm3IRZFwBW1XaX8UQ7
gamjRBK7e/BfMydXWlkr3TAdYFOGfzwwgHEfG/EVh7C7KYQnayaF53ViEOSz+JVT
hCMEVYxvUQyR4PxWtdGIX/KUnpWka8G+4fpx9QJ+EMRDSOkdD9dED0Z6JyISEuiP
XGumQpbK4NIHv8YPiMfPtcRaoYOdGMS3xFhD5UJqSpDIARZCj5U8NZxKwGA0UvrA
tzYeL9NdZihakhRdT8oBWPg31wtLzRGOSipBVEON8xDESpobmepBWQcmeoiwYkJB
V5wXIvRulhwuPspUXJlWUXF10ZuAdBJdo5WT0GSQ1xQsAOiNLbBH6YmL23rLftkH
9uMEFswN5UokLAohJjAvXVTIw8Zqvwg8eXlFtQZ8qkK9LgwZypdQblB6sKXJ9WM3
CEmcGfJK7FE705A6XXO27EmR98cuuZHBw3iJgFyx6jigzAIXayfFjWOM5aMmaEV8
+bm+AnygiUBXlxlclUEC6JlnFusq2CNFO2BbhVNwsbIbOTLN7UFgqplzx+uuWsr2
TZTPfMlQbwd7rXMBLbtKyBQKOHrkEuszyVFFliBfchY1hiIX2bYJGMYmjZNEkVuE
eiR2waJw8VSlyEI0FlrPyGk5hwL0qemgfnsoMeqb3LeEH+nA+iXIM4CSVho+3dxw
Afr4rWV4GmAqqtFl2baXmtrESKRGL1ZGhVJ/diQ0/ppCWorDe0VzkuyoDJE1BhUe
OhMjnzQvynZVtuquhFoiHOS+Z/VjnGGT9v3u9X45m4CLfzqitXQKre2QFj3F13XJ
+vfx+9B12rNE6dfRRmRygfuezzWYv1YM7epMOxCBfDptd2T+gdeg==
-----END PUBLIC KEY-----

```

Appendix E. ASN.1 Module

This appendix includes the ASN.1 module [X680] for X-Wing.

```

<CODE BEGINS>
XWing-KEM-2024
{ iso(1) member-body(2) us(840) rsadsi(113549) pkcs(1)
  pkcs-9(9) smime(16) modules(0) id-mod-XWing-kem-2024(TBD) }

DEFINITIONS IMPLICIT TAGS ::= BEGIN

-- EXPORTS ALL;

IMPORTS

```

```
KEM-ALGORITHM
  FROM KEMAlgorithmInformation-2023 -- [I-D.housley-lamps-cms-kemri]
    { iso(1) identified-organization(3) dod(6) internet(1)
      security(5) mechanisms(5) pkix(7) id-mod(0)
      id-mod-kemAlgorithmInformation-2023(109) }

AlgorithmIdentifier{}, PUBLIC-KEY, SMIME-CAPS
  FROM AlgorithmInformation-2009 -- [RFC5912]
    { iso(1) identified-organization(3) dod(6) internet(1)
      security(5) mechanisms(5) pkix(7) id-mod(0)
      id-mod-algorithmInformation-02(58) } ;

-- XWing KEM Algorithm

id-XWing OBJECT IDENTIFIER ::= { iso(1) identified-organization(3)
  dod(6) internet(1) private(4) enterprise(1) 62253 25722 }

XWingPublicKey ::= OCTET STRING

kema-XWing KEM-ALGORITHM ::= {
  IDENTIFIER id-XWing
  PARAMS ARE absent
  PUBLIC-KEYS { pk-XWing }
  UKM ARE optional
  SMIME-CAPS { IDENTIFIED BY id-XWing } }

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

-- Updates for the KEM-ALGORITHM Set from rfc5990bis

KeyEncapsulationMechanism ::=
  AlgorithmIdentifier { KEM-ALGORITHM, {KEMAlgorithms} }

KEMAlgorithms KEM-ALGORITHM ::= { kema-XWing, ... }

-- Updates for the SMIME-CAPS Set from RFC 5911

SMimeCapsSet SMIME-CAPS ::= {kema-XWing.&smimeCaps, ... }

END
```

<CODE ENDS>

Appendix F. Acknowledgments

TODO acknowledge.

Appendix G. Change log

RFC Editor's Note: Please remove this section prior to publication of a final version of this document.

G.1. Since draft-connolly-cfrg-xwing-kem-07

- * Elaborate on relation between randomized and derandomized functions.
- * Update implementations section.

G.2. Since draft-connolly-cfrg-xwing-kem-06

- * Add asn.1 module.
- * To match FIPS 202, we request number of bits from SHAKE-256 instead of number of bytes. #27
- * Update implementations section.
- * Correct PEM header. #25

G.3. Since draft-connolly-cfrg-xwing-kem-05

- * Fix several typos.
- * Change HPKE/TLS codepoint requests to the memorable 25519 + 203.
- * Add instruction for use in X.509. #21

G.4. Since draft-connolly-cfrg-xwing-kem-04

- * Note that ML-KEM decapsulation key check is not required.
- * Properly refer to FIPS 203 dependencies. #20
- * Move label at the end. As everything fits within a single block of SHA3-256, this does not make any difference.

- * Use SHAKE-256 to stretch seed. This does not have any security or performance effects: as we only squeeze 96 bytes, we perform a single Keccak permutation whether SHAKE-128 or SHAKE-256 is used. The effective capacity of the sponge in both cases is 832, which gives a security of 416 bits. It does require less thought from anyone analysing X-Wing in a rush.
- * Add HPKE codepoint.
- * Don't mark TLS entry as recommended before it has been through the IETF consensus process. (Obviously the authors recommend X-Wing.)

G.5. Since draft-connolly-cfrg-xwing-kem-03

- * Mandate ML-KEM encapsulation key check, and stipulate effect on TLS and HPKE integration.
- * Add provisional TLS codepoint. (Not assigned, yet.)

G.6. Since draft-connolly-cfrg-xwing-kem-02

- * Use seed as private key.
- * Expand on caching decapsulation key values.
- * Expand on binding properties.

G.7. Since draft-connolly-cfrg-xwing-kem-01

- * Add list of implementations.
- * Miscellaneous editorial improvements.
- * Add Python reference specification.
- * Correct definition of ML-KEM-768.KeyGenDerand(seed).

G.8. Since draft-connolly-cfrg-xwing-kem-00

- * A copy of the X25519 public key is now included in the X-Wing decapsulation (private) key, so that decapsulation does not require separate access to the X-Wing public key. See #2.

Authors' Addresses

Deirdre Connolly
SandboxAQ
Email: durumcrustulum@gmail.com

Peter Schwabe
MPI-SP & Radboud University
Email: peter@cryptojedi.org

Bas Westerbaan
Cloudflare
Email: bas@cloudflare.com