             CFRG Elliptic Curve Diffie-Hellman (ECDH) and Signatures
                 in JSON Object Signing and Encryption (JOSE)

Abstract

   This document defines how to use the Diffie-Hellman algorithms
   "X25519" and "X448" as well as the signature algorithms "Ed25519" and
   "Ed448" from the IRTF CFRG elliptic curves work in JSON Object
   Signing and Encryption (JOSE).

Status of This Memo

   This is an Internet Standards Track document.

   This document is a product of the Internet Engineering Task Force
   (IETF). It represents the consensus of the IETF community. It has
   received public review and has been approved for publication by the
   Internet Engineering Steering Group (IESG). Further information on
   Internet Standards is available in Section 2 of RFC 7841.

   Information about the current status of this document, any errata,
   and how to provide feedback on it may be obtained at
   http://www.rfc-editor.org/info/rfc8037.

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1. Introduction

   The Internet Research Task Force (IRTF) Crypto Forum Research Group
   (CFRG) selected new Diffie-Hellman algorithms ("X25519" and "X448";
   [RFC7748]) and signature algorithms ("Ed25519" and "Ed448";
   [RFC8032]) for asymmetric key cryptography. This document defines
   how to use those algorithms in JOSE in an interoperable manner.

   This document defines the conventions to use in the context of
   [RFC7515], [RFC7516], and [RFC7517].

   While the CFRG also defined two pairs of isogenous elliptic curves
   that underlie these algorithms, these curves are not directly
   exposed, as the algorithms laid on top are sufficient for the
   purposes of JOSE and are much easier to use.

   All inputs to and outputs from the Elliptic Curve Diffie-Hellman
   (ECDH) and signature functions are defined to be octet strings, with
   the exception of outputs of verification functions, which are
   booleans.

1.1. Terminology

   The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT",
   "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this
   document are to be interpreted as described in [RFC2119].

   "JWS Signing Input" and "JWS Signature" are defined by [RFC7515].

   "Key Agreement with Elliptic Curve Diffie-Hellman Ephemeral Static"
   is defined by Section 4.6 of [RFC7518].

   The JOSE key format ("JSON Web Key (JWK)") is defined by [RFC7517]
   and thumbprints for it ("JSON Web Key (JWK) Thumbprint") in
   [RFC7638].

2. Key Type "OKP"

   A new key type (kty) value "OKP" (Octet Key Pair) is defined for
   public key algorithms that use octet strings as private and public
   keys. It has the following parameters:

   o   The parameter "kty" MUST be "OKP".

   o   The parameter "crv" MUST be present and contain the subtype of the
       key (from the "JSON Web Elliptic Curve" registry).

   o   The parameter "x" MUST be present and contain the public key
       encoded using the base64url [RFC4648] encoding.

   o   The parameter "d" MUST be present for private keys and contain the
       private key encoded using the base64url encoding. This parameter
       MUST NOT be present for public keys.

   Note: Do not assume that there is an underlying elliptic curve,
   despite the existence of the "crv" and "x" parameters. (For
   instance, this key type could be extended to represent Diffie-Hellman
   (DH) algorithms based on hyperelliptic surfaces.)

   When calculating JWK Thumbprints [RFC7638], the three public key
   fields are included in the hash input in lexicographic order: "crv",
   "kty", and "x".

3. Algorithms

3.1. Signatures

   For the purpose of using the Edwards-curve Digital Signature
   Algorithm (EdDSA) for signing data using "JSON Web Signature (JWS)"
   [RFC7515], algorithm "EdDSA" is defined here, to be applied as the
   value of the "alg" parameter.

   The following key subtypes are defined here for use with EdDSA:

      "crv"   EdDSA Variant
      Ed25519   Ed25519
      Ed448   Ed448

   The key type used with these keys is "OKP" and the algorithm used for
   signing is "EdDSA". These subtypes MUST NOT be used for Elliptic
   Curve Diffie-Hellman Ephemeral Static (ECDH-ES).

   The EdDSA variant used is determined by the subtype of the key
   (Ed25519 for "Ed25519" and Ed448 for "Ed448").

3.1.1. Signing

   Signing for these is performed by applying the signing algorithm
   defined in [RFC8032] to the private key (as private key), public key
   (as public key), and the JWS Signing Input (as message). The
   resulting signature is the JWS Signature. All inputs and outputs are
   octet strings.

3.1.2. Verification

   Verification is performed by applying the verification algorithm
   defined in [RFC8032] to the public key (as public key), the JWS
   Signing Input (as message), and the JWS Signature (as signature).
   All inputs are octet strings. If the algorithm accepts, the
   signature is valid; otherwise, the signature is invalid.

3.2. ECDH-ES

   The following key subtypes are defined here for purpose of "Key
   Agreement with Elliptic Curve Diffie-Hellman Ephemeral Static"
   (ECDH-ES):

      "crv"   ECDH Function Applied
      X25519   X25519
      X448   X448

The key type used with these keys is "OKP". These subtypes MUST NOT
be used for signing.

Section 4.6 of [RFC7518] defines the ECDH-ES algorithms
"ECDH-ES+A128KW", "ECDH-ES+A192KW", "ECDH-ES+A256KW", and "ECDH-ES".

3.2.1. Performing the ECDH Operation

The "x" parameter of the "epk" field is set as follows:

Apply the appropriate ECDH function to the ephemeral private key (as
scalar input) and the standard base point (as u-coordinate input).
The base64url encoding of the output is the value for the "x"
parameter of the "epk" field. All inputs and outputs are octet
strings.

The Z value (raw key agreement output) for key agreement (to be used
in subsequent Key Derivation Function (KDF) as per Section 4.6.2 of
[RFC7518]) is determined as follows:

Apply the appropriate ECDH function to the ephemeral private key (as
scalar input) and receiver public key (as u-coordinate input). The
output is the Z value. All inputs and outputs are octet strings.

4. Security Considerations

Security considerations from [RFC7748] and [RFC8032] apply here.

Do not separate key material from information about what key subtype
it is for. When using keys, check that the algorithm is compatible
with the key subtype for the key. To do otherwise opens the system
up to attacks via mixing up algorithms. It is particularly dangerous
to mix up signature and Message Authentication Code (MAC) algorithms.

Although for Ed25519 and Ed448, the signature binds the key used for
signing, do not assume this, as there are many signature algorithms
that fail to make such a binding. If key-binding is desired, include
the key used for signing either inside the JWS protected header or
the data to sign.

If key generation or batch signature verification is performed, a
well-seeded cryptographic random number generator is REQUIRED.
Signing and non-batch signature verification are deterministic
operations and do not need random numbers of any kind.

The JSON Web Algorithm (JWA) ECDH-ES KDF construction does not mix
keys into the final shared secret. In key exchange, such mixing
could be a bad mistake; whereas here either the receiver public key
has to be chosen maliciously or the sender has to be malicious in
order to cause problems. In either case, all security evaporates.

The nominal security strengths of X25519 and X448 are ~126 and ~223
bits. Therefore, using 256-bit symmetric encryption (especially key
wrapping and encryption) with X448 is RECOMMENDED.

5. IANA Considerations

The following has been added to the "JSON Web Key Types" registry:

o "kty" Parameter Value: "OKP"
o Key Type Description: Octet string key pairs
o JOSE Implementation Requirements: Optional
o Change Controller: IESG
o Specification Document(s): Section 2 of RFC 8037

The following has been added to the "JSON Web Key Parameters"
registry:

o Parameter Name: "crv"
o Parameter Description: The subtype of key pair
o Parameter Information Class: Public
o Used with "kty" Value(s): "OKP"
o Change Controller: IESG
o Specification Document(s): Section 2 of RFC 8037

o Parameter Name: "d"
o Parameter Description: The private key
o Parameter Information Class: Private
o Used with "kty" Value(s): "OKP"
o Change Controller: IESG
o Specification Document(s): Section 2 of RFC 8037

o Parameter Name: "x"
o Parameter Description: The public key
o Parameter Information Class: Public
o Used with "kty" Value(s): "OKP"
o Change Controller: IESG
o Specification Document(s): Section 2 of RFC 8037

The following has been added to the "JSON Web Signature and
Encryption Algorithms" registry:

o Algorithm Name: "EdDSA"
o Algorithm Description: EdDSA signature algorithms
o Algorithm Usage Location(s): "alg"
o JOSE Implementation Requirements: Optional
o Change Controller: IESG

o Specification Document(s): Section 3.1 of RFC 8037
o Algorithm Analysis Documents(s): [RFC8032]

The following has been added to the "JSON Web Key Elliptic Curve"
registry:

o Curve Name: "Ed25519"
o Curve Description: Ed25519 signature algorithm key pairs
o JOSE Implementation Requirements: Optional
o Change Controller: IESG
o Specification Document(s): Section 3.1 of RFC 8037

o Curve Name: "Ed448"
o Curve Description: Ed448 signature algorithm key pairs
o JOSE Implementation Requirements: Optional
o Change Controller: IESG
o Specification Document(s): Section 3.1 of RFC 8037

o Curve name: "X25519"
o Curve Description: X25519 function key pairs
o JOSE Implementation Requirements: Optional
o Change Controller: IESG
o Specification Document(s): Section 3.2 of RFC 8037
o Analysis Documents(s): [RFC7748]

o Curve Name: "X448"
o Curve Description: X448 function key pairs
o JOSE Implementation Requirements: Optional
o Change Controller: IESG
o Specification Document(s): Section 3.2 of RFC 8037
o Analysis Documents(s): [RFC7748]

6. References

6.1. Normative References

   [RFC2119] Bradner, S., "Key words for use in RFCs to Indicate
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              <http://www.rfc-editor.org/info/rfc2119>.

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   [RFC7515] Jones, M., Bradley, J., and N. Sakimura, "JSON Web
              Signature (JWS)", RFC 7515, DOI 10.17487/RFC7515, May
              2015, <http://www.rfc-editor.org/info/rfc7515>.

   [RFC7517] Jones, M., "JSON Web Key (JWK)", RFC 7517,
              DOI 10.17487/RFC7517, May 2015,
              <http://www.rfc-editor.org/info/rfc7517>.

   [RFC7518] Jones, M., "JSON Web Algorithms (JWA)", RFC 7518,
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              <http://www.rfc-editor.org/info/rfc7518>.

   [RFC7638] Jones, M. and N. Sakimura, "JSON Web Key (JWK)
              Thumbprint", RFC 7638, DOI 10.17487/RFC7638, September
              2015, <http://www.rfc-editor.org/info/rfc7638>.

   [RFC7748] Langley, A., Hamburg, M., and S. Turner, "Elliptic Curves
              for Security", RFC 7748, DOI 10.17487/RFC7748, January
              2016, <http://www.rfc-editor.org/info/rfc7748>.

   [RFC8032] Josefsson, S. and I. Liusvaara, "Edwards-Curve Digital
              Signature Algorithm (EdDSA)", RFC 8032,
              DOI 10.17487/RFC8032, January 2017,
              <http://www.rfc-editor.org/info/rfc8032>.

6.2. Informative References

   [RFC7516] Jones, M. and J. Hildebrand, "JSON Web Encryption (JWE)",
              RFC 7516, DOI 10.17487/RFC7516, May 2015,
              <http://www.rfc-editor.org/info/rfc7516>.

Appendix A. Examples

   To the extent possible, these examples use material taken from test
   vectors of [RFC7748] and [RFC8032].

A.1. Ed25519 Private Key

   {"kty":"OKP","crv":"Ed25519",
   "d":"nWGxne_9WmC6hEr0kuwsxERJxWl7MmkZcDusAxyuf2A",
   "x":"11qYAYKxCrfVS_7TyWQHOg7hcvPapiMlrwIaaPcHURo"}

   The hexadecimal dump of private key is:

   9d 61 b1 9d ef fd 5a 60 ba 84 4a f4 92 ec 2c c4
   44 49 c5 69 7b 32 69 19 70 3b ac 03 1c ae 7f 60

   And of the public key is:

   d7 5a 98 01 82 b1 0a b7 d5 4b fe d3 c9 64 07 3a
   0e e1 72 f3 da a6 23 25 af 02 1a 68 f7 07 51 1a

A.2. Ed25519 Public Key

   This is the public part of the previous private key (which just omits
   "d"):

   {"kty":"OKP","crv":"Ed25519",
   "x":"11qYAYKxCrfVS_7TyWQHOg7hcvPapiMlrwIaaPcHURo"}

A.3. JWK Thumbprint Canonicalization

   The JWK Thumbprint canonicalization of the two examples above (with a
   linebreak inserted for formatting reasons) is:

   {"crv":"Ed25519","kty":"OKP","x":"11qYAYKxCrfVS_7TyWQHOg7hcvPapiMlrwI
   aaPcHURo"}

   Which has the SHA-256 hash (in hexadecimal) of
   90facafea9b1556698540f70c0117a22ea37bd5cf3ed3c47093c1707282b4b89,
   which results in the base64url encoded JWK Thumbprint representation
   of "kPrK_qmxVWaYVA9wwBF6Iuo3vVzz7TxHCTwXBygrS4k".

A.4. Ed25519 Signing

   The JWS protected header is:

   {"alg":"EdDSA"}

   This has the base64url encoding of:

   eyJhbGciOiJFZERTQSJ9

   The payload is (text):

   Example of Ed25519 signing

   This has the base64url encoding of:

   RXhhbXBsZSBvZiBFZDI1NTE5IHNpZ25pbmc

   The JWS signing input is (a concatenation of base64url encoding of
   the (protected) header, a dot, and base64url encoding of the payload)
   is:

   eyJhbGciOiJFZERTQSJ9.RXhhbXBsZSBvZiBFZDI1NTE5IHNpZ25pbmc

   Applying the Ed25519 signing algorithm using the private key, public
   key, and the JWS signing input yields the signature (hex):

   86 0c 98 d2 29 7f 30 60 a3 3f 42 73 96 72 d6 1b
   53 cf 3a de fe d3 d3 c6 72 f3 20 dc 02 1b 41 1e
   9d 59 b8 62 8d c3 51 e2 48 b8 8b 29 46 8e 0e 41
   85 5b 0f b7 d8 3b b1 5b e9 02 bf cc b8 cd 0a 02

   Converting this to base64url yields:

   hgyY0il_MGCjP0JzlnLWG1PPOt7-09PGcvMg3AIbQR6dWbhijcNR4ki4iylGjg5BhVsPt
   9g7sVvpAr_MuM0KAg

   So the compact serialization of the JWS is (a concatenation of
   signing input, a dot, and base64url encoding of the signature):

   eyJhbGciOiJFZERTQSJ9.RXhhbXBsZSBvZiBFZDI1NTE5IHNpZ25pbmc.hgyY0il_MGCj
   P0JzlnLWG1PPOt7-09PGcvMg3AIbQR6dWbhijcNR4ki4iylGjg5BhVsPt9g7sVvpAr_Mu
   M0KAg

A.5. Ed25519 Validation

   The JWS from the example above is:

   eyJhbGciOiJFZERTQSJ9.RXhhbXBsZSBvZiBFZDI1NTE5IHNpZ25pbmc.hgyY0il_MGCj
   P0JzlnLWG1PPOt7-09PGcvMg3AIbQR6dWbhijcNR4ki4iylGjg5BhVsPt9g7sVvpAr_Mu
   M0KAg

   This has 2 dots in it, so it might be valid a JWS. Base64url
   decoding the protected header yields:

   {"alg":"EdDSA"}

   So this is an EdDSA signature. Now the key has: "kty":"OKP" and
   "crv":"Ed25519", so the signature is Ed25519 signature.

   The signing input is the part before the second dot:

   eyJhbGciOiJFZERTQSJ9.RXhhbXBsZSBvZiBFZDI1NTE5IHNpZ25pbmc

   Applying the Ed25519 verification algorithm to the public key, JWS
   signing input, and the signature yields true. So the signature is
   valid. The message is the base64url decoding of the part between the
   dots:

   Example of Ed25519 Signing

A.6. ECDH-ES with X25519

   The public key to encrypt to is:

   {"kty":"OKP","crv":"X25519","kid":"Bob",
   "x":"3p7bfXt9wbTTW2HC7OQ1Nz-DQ8hbeGdNrfx-FG-IK08"}

   The public key from the target key is (hex):

   de 9e db 7d 7b 7d c1 b4 d3 5b 61 c2 ec e4 35 37
   3f 83 43 c8 5b 78 67 4d ad fc 7e 14 6f 88 2b 4f

   The ephemeral secret happens to be (hex):

   77 07 6d 0a 73 18 a5 7d 3c 16 c1 72 51 b2 66 45
   df 4c 2f 87 eb c0 99 2a b1 77 fb a5 1d b9 2c 2a

   So the ephemeral public key is X25519(ephkey, G) (hex):

   85 20 f0 09 89 30 a7 54 74 8b 7d dc b4 3e f7 5a
   0d bf 3a 0d 26 38 1a f4 eb a4 a9 8e aa 9b 4e 6a

This is represented as the ephemeral public key value:

```
{"kty":"OKP","crv":"X25519",
"x":"hSDwCYkwp1R0i33ctD73Wg2_Og0mOBr066SpjqqbTmo"}
```

So the protected header could be, for example:

```
{"alg":"ECDH-ES+A128KW","epk":{"kty":"OKP","crv":"X25519",
"x":"hSDwCYkwp1R0i33ctD73Wg2_Og0mOBr066SpjqqbTmo"},
"enc":"A128GCM","kid":"Bob"}
```

And the sender computes the DH Z value as X25519(ephkey, recv_pub) (hex):

```
4a 5d 9d 5b a4 ce 2d e1 72 8e 3b f4 80 35 0f 25
e0 7e 21 c9 47 d1 9e 33 76 f0 9b 3c 1e 16 17 42
```

The receiver computes the DH Z value as X25519(seckey, ephkey_pub) (hex):

```
4a 5d 9d 5b a4 ce 2d e1 72 8e 3b f4 80 35 0f 25
e0 7e 21 c9 47 d1 9e 33 76 f0 9b 3c 1e 16 17 42
```

This is the same as the sender's value (both sides run this through the KDF before using it as a direct encryption key or AES128-KW key).

A.7. ECDH-ES with X448

The public key to encrypt to (with a linebreak inserted for formatting reasons) is:

```
{"kty":"OKP","crv":"X448","kid":"Dave",
"x":"PreoKbDNIPW8_AtZm2_sz22kYnEHvbDU80W0MCfYuXL8PjT7QjKhPKcG3LV67D2
uB73BxnvzNgk"}
```

The public key from the target key is (hex):

```
3e b7 a8 29 b0 cd 20 f5 bc fc 0b 59 9b 6f ec cf
6d a4 62 71 07 bd b0 d4 f3 45 b4 30 27 d8 b9 72
fc 3e 34 fb 42 32 a1 3c a7 06 dc b5 7a ec 3d ae
07 bd c1 c6 7b f3 36 09
```

The ephemeral secret happens to be (hex):

```
9a 8f 49 25 d1 51 9f 57 75 cf 46 b0 4b 58 00 d4
ee 9e e8 ba e8 bc 55 65 d4 98 c2 8d d9 c9 ba f5
74 a9 41 97 44 89 73 91 00 63 82 a6 f1 27 ab 1d
9a c2 d8 c0 a5 98 72 6b
```

So the ephemeral public key is X448(ephkey, G) (hex):

```
9b 08 f7 cc 31 b7 e3 e6 7d 22 d5 ae a1 21 07 4a
27 3b d2 b8 3d e0 9c 63 fa a7 3d 2c 22 c5 d9 bb
c8 36 64 72 41 d9 53 d4 0c 5b 12 da 88 12 0d 53
17 7f 80 e5 32 c4 1f a0
```

This is packed into the ephemeral public key value (a linebreak inserted for formatting purposes):

```
{"kty":"OKP","crv":"X448",
"x":"mwj3zDG34-Z9ItWuoSEHSic70rg94Jxj-qc9LCLF2bvINmRyQdlT1AxbEtqIEg1
TF3-A5TLEH6A"}
```

So the protected header could be, for example (a linebreak inserted for formatting purposes):

```
{"alg":"ECDH-ES+A256KW","epk":{"kty":"OKP","crv":"X448",
"x":"mwj3zDG34-Z9ItWuoSEHSic70rg94Jxj-qc9LCLF2bvINmRyQdlT1AxbEtqIEg1
TF3-A5TLEH6A"},"enc":"A256GCM","kid":"Dave"}
```

And the sender computes the DH Z value as X448(ephkey,recv_pub) (hex):

```
07 ff f4 18 1a c6 cc 95 ec 1c 16 a9 4a 0f 74 d1
2d a2 32 ce 40 a7 75 52 28 1d 28 2b b6 0c 0b 56
fd 24 64 c3 35 54 39 36 52 1c 24 40 30 85 d5 9a
44 9a 50 37 51 4a 87 9d
```

The receiver computes the DH Z value as X448(seckey, ephkey_pub) (hex):

```
07 ff f4 18 1a c6 cc 95 ec 1c 16 a9 4a 0f 74 d1
2d a2 32 ce 40 a7 75 52 28 1d 28 2b b6 0c 0b 56
fd 24 64 c3 35 54 39 36 52 1c 24 40 30 85 d5 9a
44 9a 50 37 51 4a 87 9d
```

This is the same as the sender's value (both sides run this through KDF before using it as the direct encryption key or AES256-KW key).

Acknowledgements

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