

CFRG  
Internet-Draft  
Intended status: Informational  
Expires: February 17, 2016

A. Langley  
Google  
M. Hamburg  
Rambus Cryptography Research  
S. Turner  
IECA, Inc.  
August 16, 2015

**Elliptic Curves for Security**  
**draft-irtf-cfrg-curves-03**

Abstract

This memo specifies two elliptic curves over prime fields that offer high practical security in cryptographic applications, including Transport Layer Security (TLS). These curves are intended to operate at the ~128-bit and ~224-bit security level, respectively, and are generated deterministically based on a list of required properties.

Status of This Memo

This Internet-Draft is submitted in full conformance with the provisions of [BCP 78](#) and [BCP 79](#).

Internet-Drafts are working documents of the Internet Engineering Task Force (IETF). Note that other groups may also distribute working documents as Internet-Drafts. The list of current Internet-Drafts is at <http://datatracker.ietf.org/drafts/current/>.

Internet-Drafts are draft documents valid for a maximum of six months and may be updated, replaced, or obsoleted by other documents at any time. It is inappropriate to use Internet-Drafts as reference material or to cite them other than as "work in progress."

This Internet-Draft will expire on February 17, 2016.

Copyright Notice

Copyright (c) 2015 IETF Trust and the persons identified as the document authors. All rights reserved.

This document is subject to [BCP 78](#) and the IETF Trust's Legal Provisions Relating to IETF Documents (<http://trustee.ietf.org/license-info>) in effect on the date of publication of this document. Please review these documents carefully, as they describe your rights and restrictions with respect to this document. Code Components extracted from this document must

include Simplified BSD License text as described in Section 4.e of the Trust Legal Provisions and are provided without warranty as described in the Simplified BSD License.

Table of Contents

- [1. Introduction](#) . . . . . [2](#)
- [2. Requirements Language](#) . . . . . [3](#)
- [3. Notation](#) . . . . . [3](#)
- [4. Recommended Curves](#) . . . . . [3](#)
  - [4.1. Curve25519](#) . . . . . [3](#)
  - [4.2. Curve448](#) . . . . . [4](#)
- [5. The curve25519 and curve448 functions](#) . . . . . [6](#)
  - [5.1. Test vectors](#) . . . . . [9](#)
- [6. Diffie-Hellman](#) . . . . . [11](#)
  - [6.1. Curve25519](#) . . . . . [11](#)
  - [6.2. Curve448](#) . . . . . [12](#)
- [7. Deterministic Generation](#) . . . . . [13](#)
  - [7.1. p = 1 mod 4](#) . . . . . [14](#)
  - [7.2. p = 3 mod 4](#) . . . . . [14](#)
  - [7.3. Base points](#) . . . . . [15](#)
- [8. Acknowledgements](#) . . . . . [15](#)
- [9. References](#) . . . . . [16](#)
  - [9.1. Normative References](#) . . . . . [16](#)
  - [9.2. Informative References](#) . . . . . [16](#)
- Authors' Addresses . . . . . [17](#)

**1. Introduction**

Since the initial standardization of elliptic curve cryptography (ECC) in [SEC1] there has been significant progress related to both efficiency and security of curves and implementations. Notable examples are algorithms protected against certain side-channel attacks, various 'special' prime shapes that allow faster modular arithmetic, and a larger set of curve models from which to choose. There is also concern in the community regarding the generation and potential weaknesses of the curves defined by NIST [NIST].

This memo specifies two elliptic curves (curve25519 and curve448) that support constant-time, exception-free scalar multiplication that is resistant to a wide range of side-channel attacks, including timing and cache attacks. These curves are of the form that supports the fastest (currently known) complete formulas for the elliptic-curve group operations, specifically the Edwards curve  $x^2 + y^2 = 1 + dx^2y^2$  for primes  $p$  when  $p = 3 \pmod{4}$ , and the twisted Edwards curve  $-x^2 + y^2 = 1 + dx^2y^2$  when  $p = 1 \pmod{4}$ .



## **2. Requirements Language**

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 [RFC 2119](#) [[RFC2119](#)].

## **3. Notation**

Throughout this document, the following notation is used:

$p$  Denotes the prime number defining the underlying field.

$GF(p)$  The finite field with  $p$  elements.

$A$  An element in the finite field  $GF(p)$ , not equal to  $-2$  or  $2$ .

$d$  An element in the finite field  $GF(p)$ , not equal to  $0$  or  $1$ .

$P$  A generator point defined over  $GF(p)$  of prime order.

$X(P)$  The x-coordinate of the elliptic curve point  $P$  on a (twisted) Edwards curve.

$Y(P)$  The y-coordinate of the elliptic curve point  $P$  on a (twisted) Edwards curve.

$u, v$  Coordinates on a Montgomery curve.

$x, y$  Coordinates on a (twisted) Edwards curve.

## **4. Recommended Curves**

### **4.1. Curve25519**

For the ~128-bit security level, the prime  $2^{255}-19$  is recommended for performance on a wide-range of architectures. This prime is congruent to 1 mod 4 and the derivation procedure in [Section 7](#) results in the following Montgomery curve  $v^2 = u^3 + A*u^2 + u$ , called "curve25519":

$p$   $2^{255}-19$

$A$  486662

order  $2^{252} + 0x14def9dea2f79cd65812631a5cf5d3ed$

cofactor 8



The base point is  $u = 9$ ,  $v = 14781619447589544791020593568409986887264606134616475288964881837755586237401$ .

This curve is isomorphic to a twisted Edwards curve  $-x^2 + y^2 = 1 + d*x^2*y^2$ , called "edwards25519", where:

p  $2^{255}-19$

d 37095705934669439343138083508754565189542113879843219016388785533085940283555

order  $2^{252} + 0x14def9dea2f79cd65812631a5cf5d3ed$

cofactor 8

X(P) 15112221349535400772501151409588531511454012693041857206046113283949847762202

Y(P) 46316835694926478169428394003475163141307993866256225615783033603165251855960

The isomorphism maps are:

$$(u, v) = ((1+y)/(1-y), \sqrt{-1}*\sqrt{486664}*u/x)$$

$$(x, y) = (\sqrt{-1}*\sqrt{486664}*u/v, (u-1)/(u+1))$$

The Montgomery curve defined here is equal to the one defined in [[curve25519](#)] and the isomorphic twisted Edwards curve is equal to the one defined in [[ed25519](#)].

#### **4.2. Curve448**

For the ~224-bit security level, the prime  $2^{448}-2^{224}-1$  is recommended for performance on a wide-range of architectures. This prime is congruent to 3 mod 4 and the derivation procedure in [Section 7](#) results in the following Montgomery curve, called "curve448":

p  $2^{448}-2^{224}-1$

A 156326

order  $2^{446} - 0x8335dc163bb124b65129c96fde933d8d723a70aad873d6d54a7bb0d$

cofactor 4



The base point is  $u = 5, v =$   
 $3552939267855681752641275020637833348089763993877142718318808984351 \setminus$   
 $69088786967410002932673765864550910142774147268105838985595290606362.$

This curve is isomorphic to the Edwards curve  $x^2 + y^2 = 1 + d*x^2*y^2$  where:

$p \quad 2^{448} - 2^{224} - 1$

$d \quad 611975850744529176160423220965553317543219696871016626328968936415$   
 $0 \setminus 87860042636474891785599283666020414768678979989378147065462815$   
 $545017$

order  $2^{446} -$   
 $0x8335dc163bb124b65129c96fde933d8d723a70aac873d6d54a7bb0d$

cofactor 4

$X(P) \quad 345397493039729516374008604150537410266655260075183290216406970$   
 $2816 \setminus 45695073672344430481787759340633221708391583424041788924124$   
 $567700732$

$Y(P) \quad 363419362147803445274661903944002267176820680343659030140745099$   
 $5903 \setminus 06164083365386343198191849338272965044442230921818680526749$   
 $009182718$

The isomorphism maps are:

$$(u, v) = ((y-1)/(y+1), \text{sqrt}(156324)*u/x)$$

$$(x, y) = (\text{sqrt}(156324)*u/v, (1+u)/(1-u))$$

That curve is also 4-isogenous to the following Edward's curve  $x^2 + y^2 = 1 + d*x^2*y^2$ , called "edwards448", where:

$p \quad 2^{448} - 2^{224} - 1$

$d \quad -39081$

order  $2^{446} -$   
 $0x8335dc163bb124b65129c96fde933d8d723a70aac873d6d54a7bb0d$

cofactor 4

The 4-isogeny maps between the Montgomery curve this the Edward's curve are:



$$\begin{aligned}
 (u, v) &= (x^2/y^2, (2 - x^2 - y^2)*x/y^3) \\
 (x, y) &= (4*v*(u^2 - 1)/(u^4 - 2*u^2 + 4*v^2 + 1), \\
 &\quad (u^5 - 2*u^3 - 4*u*v^2 + u)/(u^5 - 2*u^2*v^2 - 2*u^3 - 2*v^2 + u))
 \end{aligned}$$

## 5. The curve25519 and curve448 functions

The "curve25519" and "curve448" functions perform scalar multiplication on the Montgomery form of the above curves. (This is used when implementing Diffie-Hellman.) The functions take a scalar and a u-coordinate as inputs and produce a u-coordinate as output. Although the functions work internally with integers, the inputs and outputs are 32-byte or 56-byte strings and this specification defines their encoding.

U-coordinates are elements of the underlying field  $GF(2^{255-19})$  or  $GF(2^{448}-2^{224}-1)$  and are encoded as an array of bytes,  $u$ , in little-endian order such that  $u[0] + 256*u[1] + 256^2*u[2] + \dots + 256^n*u[n]$  is congruent to the value modulo  $p$  and  $u[n]$  is minimal. When receiving such an array, implementations of curve25519 (but not curve448) MUST mask the most-significant bit in the final byte. This is done to preserve compatibility with point formats which reserve the sign bit for use in other protocols and to increase resistance to implementation fingerprinting.

Implementations MUST accept non-canonical values and process them as if they had been reduced modulo the field prime. The non-canonical values are  $2^{255-19}$  through  $2^{255}-1$  for curve25519 and  $2^{448}-2^{224}-1$  through  $2^{448}-1$  for curve448.

The following functions implement this in Python, although the Python code is not intended to be performant nor side-channel free. Here the "bits" parameter should be set to 255 for curve25519 and 448 for curve448:

```

def decodeLittleEndian(b, bits):
    return sum([b[i] << 8*i for i in range((bits+7)/8)])

def decodeUCoordinate(u, bits):
    u_list = [ord(b) for b in u]
    # Ignore any unused bits
    if bits % 8:
        u_list[-1] &= (1<<(bits%8))-1
    return decodeLittleEndian(u_list, bits)

def encodeUCoordinate(u, bits):
    u = u % p
    return ''.join([chr((u >> 8*i) & 0xff) for i in range((bits+7)/8)])

```



Scalars are assumed to be randomly generated bytes. For curve25519, in order to decode 32 random bytes as an integer scalar, set the three least significant bits of the first byte and the most significant bit of the last to zero, set the second most significant bit of the last byte to 1 and, finally, decode as little-endian. This means that resulting integer is of the form  $2^{254} + 8 * \{0, 1, \dots, 2^{(251)} - 1\}$ . Likewise, for curve448, set the two least significant bits of the first byte to 0, and the most significant bit of the last byte to 1. This means that the resulting integer is of the form  $2^{447} + 4 * \{0, 1, \dots, 2^{(445)} - 1\}$ .

```
def decodeScalar25519(k):
    k_list = [ord(b) for b in k]
    k_list[0] &= 248
    k_list[31] &= 127
    k_list[31] |= 64
    return decodeLittleEndian(k_list, 255)
```

```
def decodeScalar448(k):
    k_list = [ord(b) for b in k]
    k_list[0] &= 252
    k_list[55] |= 128
    return decodeLittleEndian(k_list, 448)
```

To implement the "curve25519(k, u)" and "curve448(k, u)" functions (where "k" is the scalar and "u" is the u-coordinate) first decode "k" and "u" and then perform the following procedure, which is taken from [\[curve25519\]](#) and based on formulas from [\[montgomery\]](#). All calculations are performed in GF(p), i.e., they are performed modulo p. The constant a24 is  $(486662 - 2) / 4 = 121665$  for curve25519 and  $(156326 - 2) / 4 = 39081$  for curve448.



```

x_1 = u
x_2 = 1
z_2 = 0
x_3 = u
z_3 = 1
swap = 0

```

For t = bits-1 down to 0:

```

k_t = (k >> t) & 1
swap ^= k_t
// Conditional swap; see text below.
(x_2, x_3) = cswap(swap, x_2, x_3)
(z_2, z_3) = cswap(swap, z_2, z_3)
swap = k_t

```

```

A = x_2 + z_2
AA = A^2
B = x_2 - z_2
BB = B^2
E = AA - BB
C = x_3 + z_3
D = x_3 - z_3
DA = D * A
CB = C * B
x_3 = (DA + CB)^2
z_3 = x_1 * (DA - CB)^2
x_2 = AA * BB
z_2 = E * (AA + a24 * E)

```

// Conditional swap; see text below.

```

(x_2, x_3) = cswap(swap, x_2, x_3)
(z_2, z_3) = cswap(swap, z_2, z_3)
Return x_2 * (z_2^(p - 2))

```

(Note that these formulas are slightly different from Montgomery's original paper. Implementations are free to use any correct formulas.)

Finally, encode the resulting value as 32 or 56 bytes in little-endian order. For curve25519, the unused, most-significant bit MUST be zero.

When implementing this procedure, due to the existence of side-channels in commodity hardware, it is important that the pattern of memory accesses and jumps not depend on the values of any of the bits of "k". It is also important that the arithmetic used not leak information about the integers modulo p (such as having b\*c be distinguishable from c\*c).



The `cswap` function SHOULD be implemented in constant time (i.e. independent of the "swap" argument). For example, this can be done as follows:

```
cswap(swap, x_2, x_3):
    dummy = mask(swap) AND (x_2 XOR x_3)
    x_2 = x_2 XOR dummy
    x_3 = x_3 XOR dummy
    Return (x_2, x_3)
```

Where "mask(swap)" is the all-1 or all-0 word of the same length as `x_2` and `x_3`, computed, e.g., as `mask(swap) = 0 - swap`.

### 5.1. Test vectors

Two types of tests are provided. The first is a pair of test vectors for each function that consist of expected outputs for the given inputs:

curve25519:

Input scalar:

a546e36bf0527c9d3b16154b82465edd62144c0ac1fc5a18506a2244ba449ac4

Input scalar as a number (base 10):

31029842492115040904895560451863089656472772604678260265531221036453811406496

Input U-coordinate:

e6db6867583030db3594c1a424b15f7c726624ec26b3353b10a903a6d0ab1c4c

Input U-coordinate as a number:

34426434033919594451155107781188821651316167215306631574996226621102155684838

Output U-coordinate:

c3da55379de9c6908e94ea4df28d084f32eccf03491c71f754b4075577a28552

Input scalar:

4b66e9d4d1b4673c5ad22691957d6af5c11b6421e0ea01d42ca4169e7918ba0d

Input scalar as a number (base 10):

35156891815674817266734212754503633747128614016119564763269015315466259359304

Input U-coordinate:

e5210f12786811d3f4b7959d0538ae2c31dbe7106fc03c3efc4cd549c715a493

Input U-coordinate as a number:

8883857351183929894090759386610649319417338800022198945255395922347792736741

Output U-coordinate:

95cbde9476e8907d7aade45cb4b873f88b595a68799fa152e6f8f7647aac7957

curve448:

Input scalar:

3d262fddf9ec8e88495266fea19a34d28882acef045104d0d1aae121







curve25519:

After one iteration:

```
422c8e7a6227d7bca1350b3e2bb7279f7897b87bb6854b783c60e80311ae3079
```

After 1,000 iterations:

```
684cf59ba83309552800ef566f2f4d3c1c3887c49360e3875f2eb94d99532c51
```

After 1,000,000 iterations:

```
7c3911e0ab2586fd864497297e575e6f3bc601c0883c30df5f4dd2d24f665424
```

curve448:

After one iteration:

```
3f482c8a9f19b01e6c46ee9711d9dc14fd4bf67af30765c2ae2b846a
```

```
4d23a8cd0db897086239492caf350b51f833868b9bc2b3bca9cf4113
```

After 1,000 iterations:

```
aa3b4749d55b9daf1e5b00288826c467274ce3ebbdd5c17b975e09d4
```

```
af6c67cf10d087202db88286e2b79fcee3ec353ef54faa26e219f38
```

After 1,000,000 iterations:

```
077f453681caca3693198420bbe515cae0002472519b3e67661a7e89
```

```
cab94695c8f4bcd66e61b9b9c946da8d524de3d69bd9d9d66b997e37
```

## **6. Diffie-Hellman**

### **6.1. Curve25519**

The "curve25519" function can be used in an elliptic-curve Diffie-Hellman (ECDH) protocol as follows:

Alice generates 32 random bytes in  $f[0]$  to  $f[31]$  and transmits  $K_A = \text{curve25519}(f, 9)$  to Bob, where 9 is the u-coordinate of the base point and is encoded as a byte with value 9, followed by 31 zero bytes.

Bob similarly generates 32 random bytes in  $g[0]$  to  $g[31]$  and computes  $K_B = \text{curve25519}(g, 9)$  and transmits it to Alice.

Using their generated values and the received input, Alice computes  $\text{curve25519}(f, K_B)$  and Bob computes  $\text{curve25519}(g, K_A)$ .

Both now share  $K = \text{curve25519}(f, \text{curve25519}(g, 9)) = \text{curve25519}(g, \text{curve25519}(f, 9))$  as a shared secret. Both MUST check, without leaking extra information about the value of  $K$ , whether  $K$  is the all-zero value and abort if so (see below). Alice and Bob can then use a key-derivation function, such as hashing  $K$ , to compute a key.

The check for the all-zero value results from the fact that the curve25519 function produces that value if it operates on an input



corresponding to a point with order dividing the co-factor,  $h$ , of the curve. This check is cheap and so MUST always be carried out. The check may be performed by ORing all the bytes together and checking whether the result is zero as this eliminates standard side-channels in software implementations.

Test vector:

Alice's private key,  $f$ :

```
77076d0a7318a57d3c16c17251b26645df4c2f87ebc0992ab177fba51db92c2a
```

Alice's public key,  $\text{curve25519}(f, 9)$ :

```
8520f0098930a754748b7ddcb43ef75a0dbf3a0d26381af4eba4a98eaa9b4e6a
```

Bob's private key,  $g$ :

```
5dab087e624a8a4b79e17f8b83800ee66f3bb1292618b6fd1c2f8b27ff88e0eb
```

Bob's public key,  $\text{curve25519}(g, 9)$ :

```
de9edb7d7b7dc1b4d35b61c2ece435373f8343c85b78674dadfc7e146f882b4f
```

Their shared secret,  $K$ :

```
4a5d9d5ba4ce2de1728e3bf480350f25e07e21c947d19e3376f09b3c1e161742
```

## **6.2. Curve448**

The "curve448" function can be used very much like "curve22519" function in an ECDH protocol.

If "curve448" is to be used the only differences are that Alice and Bob generate 56 random bytes (not 32) and calculate  $K_A = \text{curve448}(f, 5)$  or  $K_B = \text{curve448}(g, 5)$  where 5 is the  $u$ -coordinate of the base point and is encoded as a byte with value 5, followed by 55 zero bytes.

The test for the all-zeros result is still required.

Test vector:



Alice's private key, f:

```
9a8f4925d1519f5775cf46b04b5800d4ee9ee8bae8bc5565d498c28d
d9c9baf574a9419744897391006382a6f127ab1d9ac2d8c0a598726b
```

Alice's public key, curve448(f, 5):

```
9b08f7cc31b7e3e67d22d5aea121074a273bd2b83de09c63faa73d2c
22c5d9bbc836647241d953d40c5b12da88120d53177f80e532c41fa0
```

Bob's private key, g:

```
1c306a7ac2a0e2e0990b294470cba339e6453772b075811d8fad0d1d
6927c120bb5ee8972b0d3e21374c9c921b09d1b0366f10b65173992d
```

Bob's public key, curve448(g, 5):

```
3eb7a829b0cd20f5bcfc0b599b6feccf6da4627107bdb0d4f345b430
27d8b972fc3e34fb4232a13ca706dcb57aec3dae07bdc1c67bf33609
```

Their shared secret, K:

```
fe2d52f1ca113e5441538037dc4a9d4cb381035fb4a990ac50ac4333
63dc072301d1d4f2e82883b35103be96068c11e7c84b8fff74bb6ab0
```

## 7. Deterministic Generation

This section specifies the procedure that was used to generate the above curves; specifically it defines how to generate the parameter  $A$  of the Montgomery curve  $y^2 = x^3 + Ax^2 + x$ . This procedure is intended to be as objective as can reasonably be achieved so that it's clear that no untoward considerations influenced the choice of curve. The input to this process is  $p$ , the prime that defines the underlying field. The size of  $p$  determines the amount of work needed to compute a discrete logarithm in the elliptic curve group and choosing a precise  $p$  depends on many implementation concerns. The performance of the curve will be dominated by operations in  $GF(p)$  so carefully choosing a value that allows for easy reductions on the intended architecture is critical. This document does not attempt to articulate all these considerations.

The value  $(A-2)/4$  is used in several of the elliptic curve point arithmetic formulas. For simplicity and performance reasons, it is beneficial to make this constant small, i.e. to choose  $A$  so that  $(A-2)$  is a small integer which is divisible by four.

For each curve at a specific security level:

1. The trace of Frobenius MUST NOT be in  $\{0, 1\}$  in order to rule out the attacks described in [Smart], [AS], and [S], as in [EBP].
2. MOV Degree: the embedding degree  $k$  MUST be greater than  $(r - 1) / 100$ , as in [EBP].
3. CM Discriminant: discriminant  $D$  MUST be greater than  $2^{100}$ , as in [SC].



**7.1.  $p = 1 \pmod{4}$** 

For primes congruent to 1 mod 4, the minimal cofactors of the curve and its twist are either {4, 8} or {8, 4}. We choose a curve with the latter cofactors so that any algorithms that take the cofactor into account don't have to worry about checking for points on the twist, because the twist cofactor will be the smaller of the two.

To generate the Montgomery curve we find the minimal, positive A value, such that  $A > 2$  and  $(A-2)$  is divisible by four and where the cofactors are as desired. The "find1Mod4" function in the following Sage script returns this value given p:

```
def findCurve(prime, curveCofactor, twistCofactor):
    F = GF(prime)

    for A in xrange(3, 1e9):
        if (A-2) % 4 != 0:
            continue

        try:
            E = EllipticCurve(F, [0, A, 0, 1, 0])
        except:
            continue

        order = E.order()
        twistOrder = 2*(prime+1)-order

        if (order % curveCofactor == 0 and is_prime(order // curveCofactor) and
            twistOrder % twistCofactor == 0 and is_prime(twistOrder //
twistCofactor)):
            return A

def find1Mod4(prime):
    assert((prime % 4) == 1)
    return findCurve(prime, 8, 4)
```

Generating a curve where  $p = 1 \pmod{4}$

**7.2.  $p = 3 \pmod{4}$** 

For a prime congruent to 3 mod 4, both the curve and twist cofactors can be 4 and this is minimal. Thus we choose the curve with these cofactors and minimal, positive A such that  $A > 2$  and  $(A-2)$  is divisible by four. The "find3Mod4" function in the following Sage script returns this value given p:



```
def find3Mod4(prime):
    assert((prime % 4) == 3)
    return findCurve(prime, 4, 4)
```

Generating a curve where  $p = 3 \pmod 4$

### **7.3. Base points**

The base point for a curve is the point with minimal, positive  $u$  value that is in the correct subgroup. The "findBasepoint" function in the following Sage script returns this value given  $p$  and  $A$ :

```
def findBasepoint(prime, A):
    F = GF(prime)
    E = EllipticCurve(F, [0, A, 0, 1, 0])

    for uInt in range(1, 1e3):
        u = F(uInt)
        v2 = u^3 + A*u^2 + u
        if not v2.is_square():
            continue
        v = v2.sqrt()

        point = E(u, v)
        order = point.order()
        if order > 8 and order.is_prime():
            return point
```

Generating the base point

## **8. Acknowledgements**

This document merges "[draft-black-rpgecc-01](#)" and "[draft-turner-thecurve25519function-01](#)". The following authors of those documents wrote much of the text and figures but are not listed as authors on this document: Benjamin Black, Joppe W. Bos, Craig Costello, Patrick Longa, Michael Naehrig and Watson Ladd.

The authors would also like to thank Tanja Lange, Rene Struik and Rich Salz for their reviews and contributions.

The curve25519 function was developed by Daniel J. Bernstein in [[curve25519](#)].



## **9. References**

### **9.1. Normative References**

- [RFC2119] Bradner, S., "Key words for use in RFCs to Indicate Requirement Levels", [BCP 14](#), [RFC 2119](#), DOI 10.17487/RFC2119, March 1997, <<http://www.rfc-editor.org/info/rfc2119>>.

### **9.2. Informative References**

- [AS] Satoh, T. and K. Araki, "Fermat quotients and the polynomial time discrete log algorithm for anomalous elliptic curves", 1998.
- [curve25519] Bernstein, D., "Curve25519 -- new Diffie-Hellman speed records", 2006, <<http://www.iacr.org/cryptodb/archive/2006/PKC/3351/3351.pdf>>.
- [EBP] ECC Brainpool, "ECC Brainpool Standard Curves and Curve Generation", October 2005, <<http://www.ecc-brainpool.org/download/Domain-parameters.pdf>>.
- [ed25519] Bernstein, D., Duif, N., Lange, T., Schwabe, P., and B. Yang, "High-speed high-security signatures", 2011, <<http://ed25519.cr.yp.to/ed25519-20110926.pdf>>.
- [montgomery] Montgomery, P., "Speeding the Pollard and elliptic curve methods of factorization", 1983, <<http://www.ams.org/journals/mcom/1987-48-177/S0025-5718-1987-0866113-7/S0025-5718-1987-0866113-7.pdf>>.
- [NIST] National Institute of Standards, "Recommended Elliptic Curves for Federal Government Use", July 1999, <<http://csrc.nist.gov/groups/ST/toolkit/documents/dss/NISTReCur.pdf>>.
- [S] Semaev, I., "Evaluation of discrete logarithms on some elliptic curves", 1998.
- [SC] Bernstein, D. and T. Lange, "SafeCurves: choosing safe curves for elliptic-curve cryptography", June 2014, <<http://safecurves.cr.yp.to/>>.



[SEC1] Certicom Research, "SEC 1: Elliptic Curve Cryptography",  
September 2000,  
<[http://www.secg.org/collateral/sec1\\_final.pdf](http://www.secg.org/collateral/sec1_final.pdf)>.

[Smart] Smart, N., "The discrete logarithm problem on elliptic  
curves of trace one", 1999.

#### Authors' Addresses

Adam Langley  
Google  
345 Spear St  
San Francisco, CA 94105  
US

Email: [agl@google.com](mailto:agl@google.com)

Mike Hamburg  
Rambus Cryptography Research  
425 Market Street, 11th Floor  
San Francisco, CA 94105  
US

Email: [mike@shiftright.org](mailto:mike@shiftright.org)

Sean Turner  
IECA, Inc.  
3057 Nutley Street  
Suite 106  
Fairfax, VA 22031  
US

Email: [turners@ieca.com](mailto:turners@ieca.com)

