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A. Langley
Google
M. Hamburg
Rambus Cryptography Research
S. Turner
IECA, Inc.
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Elliptic Curves for Security
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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.

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[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 $p = 3 \bmod 4$, and the twisted Edwards curve $-x^2 + y^2 = 1 + dx^2y^2$ when $p = 1 \bmod 4$.

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[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

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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:

$$\begin{aligned}(u, v) &= ((1+y)/(1-y), \text{sqrt}(-486664)*u/x) \\ (x, y) &= (\text{sqrt}(-486664)*u/v, (u-1)/(u+1))\end{aligned}$$

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 $u = 5$, $v = 355293926785568175264127502063783334808976399387714271831880898435169088786967410002932673765864550910142774147268105838985595290606362$.

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

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

d 611975850744529176160423220965553317543219696871016626328968936415
087860042636474891785599283666020414768678979989378147065462815545
017

order $2^{446} -$
0x8335dc163bb124b65129c96fde933d8d723a70aad873d6d54a7bb0d

cofactor 4

X(P) 345397493039729516374008604150537410266655260075183290216406970
281645695073672344430481787759340633221708391583424041788924124567
700732

Y(P) 363419362147803445274661903944002267176820680343659030140745099
590306164083365386343198191849338272965044442230921818680526749009
182718

The isomorphism maps are:

$$\begin{aligned}(u, v) &= ((y-1)/(y+1), \sqrt{156324} \cdot u/x) \\ (x, y) &= (\sqrt{156324} \cdot u/v, (1+u)/(1-u))\end{aligned}$$

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

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

d -39081

order $2^{446} -$
0x8335dc163bb124b65129c96fde933d8d723a70aad873d6d54a7bb0d

cofactor 4

X(P) 224580040295924300187604334099896036246789641632564134246125461
686950415467406032909029192869357953282578032075146446173674602635
247710

Y(P) 298819210078481492676017930443930673437544040154080242095928241
372331506189835876003536878655418784733982303233503462500531545062
832660

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

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

The curve "edwards448" defined here is also called "Goldilocks" and is equal to the one defined in [[goldilocks](#)].

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):

31029842492115040904895560451863089656

472772604678260265531221036453811406496

Input U-coordinate:

e6db6867583030db3594c1a424b15f7c726624ec26b3353b10a903a6d0ab1c4c

Input U-coordinate as a number:

34426434033919594451155107781188821651

316167215306631574996226621102155684838

Output U-coordinate:

c3da55379de9c6908e94ea4df28d084f32eccf03491c71f754b4075577a28552

Input scalar:

4b66e9d4d1b4673c5ad22691957d6af5c11b6421e0ea01d42ca4169e7918ba0d

Input scalar as a number (base 10):

35156891815674817266734212754503633747

128614016119564763269015315466259359304

Input U-coordinate:

e5210f12786811d3f4b7959d0538ae2c31dbe7106fc03c3efc4cd549c715a493

Input U-coordinate as a number:

88838573511839298940907593866106493194

17338800022198945255395922347792736741

Output U-coordinate:

95cbde9476e8907d7aade45cb4b873f88b595a68799fa152e6f8f7647aac7957

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curve448:

Input scalar:

3d262fddf9ec8e88495266fea19a34d28882acef045104d0d1aae121
700a779c984c24f8cdd78fbff44943eba368f54b29259a4f1c600ad3

Input scalar as a number (base 10):

5991891753738964027837560161452132561572308560850261299268914594686 \\
22403380588640249457727683869421921443004045221642549886377526240828

Input U-coordinate:

06fce640fa3487bfda5f6cf2d5263f8aad88334cbd07437f020f08f9
814dc031ddbdc38c19c6da2583fa5429db94ada18aa7a7fb4ef8a086

Input U-coordinate as a number:

3822399108141073301162299612348993770314163652405713251483465559224 \\
38025162094455820962429142971339584360034337310079791515452463053830

Output U-coordinate:

ce3e4ff95a60dc6697da1db1d85e6afbdf79b50a2412d7546d5f239f
e14fbaadeb445fc66a01b0779d98223961111e21766282f73dd96b6f

Input scalar:

203d494428b8399352665ddca42f9de8fef600908e0d461cb021f8c5
38345dd77c3e4806e25f46d3315c44e0a5b4371282dd2c8d5be3095f

Input scalar as a number (base 10):

6332543359069705927792594815348623723825251552520289610564040013321 \\
22152890562527156973881968934311400345568203929409663925541994577184

Input U-coordinate:

0fbcc2f993cd56d3305b0b7d9e55d4c1a8fb5dbb52f8e9a1e9b6201b
165d015894e56c4d3570bee52fe205e28a78b91cdfbde71ce8d157db

Input U-coordinate as a number:

6227617977583254444629220684312341806495903900248112997616251537672 \\
28042600197997696167956134770744996690267634159427999832340166786063

Output U-coordinate:

884a02576239ff7a2f2f63b2db6a9ff37047ac13568e1e30fe63c4a7
ad1b3ee3a5700df34321d62077e63633c575c1c954514e99da7c179d

The second type of test vector consists of the result of calling the function in question a specified number of times. Initially, set "k" and "u" to be the following values:

For curve25519:

bytes.

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

Using their generated values and the received input, Alice computes `curve25519(f, K_B)` and Bob computes `curve25519(g, K_A)`.

Both now share `K = curve25519(f, curve25519(g, 9)) = curve25519(g, 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 that includes `K`, `K_A` and `K_B` to derive 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, `curve25519(f, 9)`:

8520f0098930a754748b7ddcb43ef75a0dbf3a0d26381af4eba4a98eaa9b4e6a

Bob's private key, `g`:

5dab087e624a8a4b79e17f8b83800ee66f3bb1292618b6fd1c2f8b27ff88e0eb

Bob's public key, `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, $\text{curve448}(f, 5)$:

9b08f7cc31b7e3e67d22d5aea121074a273bd2b83de09c63faa73d2c
22c5d9bbc836647241d953d40c5b12da88120d53177f80e532c41fa0

Bob's private key, g:

1c306a7ac2a0e2e0990b294470cba339e6453772b075811d8fad0d1d
6927c120bb5ee8972b0d3e21374c9c921b09d1b0366f10b65173992d

Bob's public key, $\text{curve448}(g, 5)$:

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](#)], [[satoh](#)], and [[semaev](#)], as in [[brainpool](#)].
2. MOV Degree: the embedding degree k MUST be greater than $(r - 1) / 100$, as in [[brainpool](#)].
3. CM Discriminant: discriminant D MUST be greater than 2^{100} , as in [[safecurves](#)].

[7.1.](#) $p \equiv 1 \pmod{4}$

For primes congruent to $1 \pmod{4}$, 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 $p = 1 \bmod 4$

[7.2.](#) $p = 3 \bmod 4$

For a prime congruent to $3 \bmod 4$, 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)
```


[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

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

[9.](#) References

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Authors' Addresses

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

Email: agl@google.com

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

Email: mike@shiftright.org

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

Email: turners@ieca.com

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