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M. Lochter
BSI
J. Merkle
secunet Security Networks
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Elliptic Curve Cryptography (ECC) Brainpool Standard Curves and Curve Generation

Abstract

This memo proposes several elliptic curve domain parameters over finite prime fields for use in cryptographic applications. The domain parameters are consistent with the relevant international standards, and can be used in X.509 certificates and certificate revocation lists (CRLs), for Internet Key Exchange (IKE), Transport Layer Security (TLS), XML signatures, and all applications or protocols based on the cryptographic message syntax (CMS).

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1. Introduction

Although several standards for elliptic curves and domain parameters exist (e.g., [ANSI1], [FIPS], or [SEC2]), some major issues have still not been addressed:

- o Not all parameters have been generated in a verifiably pseudo-random way. In particular, the seeds from which the curve parameters were derived have been chosen ad hoc, leaving out an essential part of the security proof.
- o The primes selected for the base fields have a very special form facilitating efficient implementation. This does not only contradict the approach of pseudo-random parameters, but also increases the risk of implementations violating one of the numerous patents for fast modular arithmetic with special primes.
- o No proofs are provided that the proposed parameters do not belong to those classes of parameters that are susceptible to cryptanalytic attacks with sub-exponential complexity.
- o Recent research results seem to indicate a potential for new attacks on elliptic curve cryptosystems. At least for applications with the highest security demands or under circumstances that complicate a change of parameters in response to new attacks, the inclusion of a corresponding security requirement for domain parameters (the class group condition, see Section 2) is justified.
- o Some of the proposed subgroups have a non-trivial cofactor, which demands additional checks by cryptographic applications to prevent small subgroup attacks (see [ANSI1] or [SEC1]).
- o The domain parameters specified do not cover all bit lengths that correspond to the commonly used key lengths for symmetric cryptographic algorithms. In particular, there is no 512-bit curve defined, but only one with a 521-bit length, which may be disadvantageous for some implementations.

Furthermore, many of the parameters specified by the existing standards are identical (see [SEC2] for a comparison). Thus, there is still a need for additional elliptic curve domain parameters that overcome the above limitations.

1.1. Scope and Relation to Other Specifications

This RFC specifies elliptic curve domain parameters over prime fields $GF(p)$ with p having a length of 160, 192, 224, 256, 320, 384, and 512 bits. These parameters were generated in a pseudo-random, yet completely systematic and reproducible, way and have been verified to resist current cryptanalytic approaches. The parameters are compliant with ANSI X9.62 [ANSI1] and ANSI X9.63 [ANSI2], ISO/IEC 14888 [ISO1] and ISO/IEC 15946 [ISO2], ETSI TS 102 176-1 [ETSI], as well as with FIPS-186-2 [FIPS], and the Efficient Cryptography Group (SECG) specifications ([SEC1] and [SEC2]).

Furthermore, this document identifies the security and implementation requirements for the parameters, and describes the methods used for the pseudo-random generation of the parameters.

Finally, this RFC defines ASN.1 object identifiers for all elliptic curve domain parameter sets specified herein, e.g., for use in X.509 certificates.

This document does neither address the cryptographic algorithms to be used with the specified parameters nor their application in other standards. However, it is consistent with the following RFCs that specify the usage of elliptic curve cryptography in protocols and applications:

- o [RFC5753] for the cryptographic message syntax (CMS)
- o [RFC3279] and [RFC5480] for X.509 certificates and CRLs
- o [RFC4050] for XML signatures
- o [RFC4492] for TLS
- o [RFC4754] for IKE

1.2. 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].

2. Requirements on the Elliptic Curve Domain Parameters

Throughout this memo, let $p > 3$ be a prime and $GF(p)$ a finite field (sometimes also referred to as Galois Field or $GF(p)$) with p elements. For given A and B with non-zero $4A^3 + 27B^2 \bmod p$, the set of solutions (x,y) for the equation $E: y^2 = x^3 + Ax + B \bmod p$

over $\text{GF}(p)$ together with a neutral element O and well-defined laws for addition and inversion define a group $E(\text{GF}(p))$ -- the group of $\text{GF}(p)$ rational points on E . Typically, for cryptographic applications, an element G of prime order q is chosen in $E(\text{GF}(p))$.

A comprehensive introduction to elliptic curve cryptography can be found in [CFDA] and [BSS].

Note 1: We choose $\{0, \dots, p-1\}$ as a set of representatives for the elements of $\text{GF}(p)$. This choice induces a natural ordering on $\text{GF}(p)$.

2.1. Security Requirements

The following security requirements are either motivated by known cryptographic analysis or aim to enhance trust in the recommended curves. As this specification aims at a particularly high level of security, a restrictive position is taken here. Nevertheless, it may be sensible to slightly deviate from these requirements for certain applications (e.g., in order to achieve higher computational performance). More details on requirements for cryptographically strong elliptic curves can be found in [CFDA] and [BSS].

1. Immunity to attacks using the Weil or Tate Pairing. These attacks allow the embedding of the cyclic subgroup generated by G into the group of units of a degree- l extension $\text{GF}(p^l)$ of $\text{GF}(p)$, where sub-exponential attacks on the discrete logarithm problem (DLP) exist. Here we have $l = \min\{t \mid q \text{ divides } p^t - 1\}$, i.e., l is the order of $p \bmod q$. By Fermat's Little Theorem, l divides $q-1$. We require $(q-1)/l < 100$, which means that l is close to the maximum possible value. This requirement is considerably stronger than those of [SEC2] and [ANSI2] and also excludes supersingular curves, as those are the curves of order $p+1$.
2. The trace is not equal to one. Trace one curves (or anomalous curves) are curves with $\#E(\text{GF}(p)) = p$. Satoh and Araki [SA], Semaev [Sem], and Smart [Sma] independently proposed efficient solutions to the elliptic curve discrete logarithm problem (ECDLP) on trace one curves. Note that these curves are also excluded by requirement 5 of Section 2.2.
3. Large class number. The class number of the maximal order of the quotient field of the endomorphism ring $\text{End}(E)$ of E is larger than 10^7 . Generally, E cannot be "lifted" to a curve E' over an algebraic number field L with $\text{End}(E) = \text{End}(E')$ unless the degree of L over the rationals is larger than the class number of $\text{End}(E)$. Although there are no efficient attacks exploiting a small class number, recent work ([JMV] and [HR]) also may be seen as argument for the class number condition.

4. Prime group order. The group order $\#E(\text{GF}(p))$ shall be a prime number in order to counter small-subgroup attacks (see [HMV]). Therefore, all groups proposed in this RFC have cofactor 1. Note that curves with prime order have no point of order 2 and therefore no point with y-coordinate 0.
5. Verifiably pseudo-random. The elliptic curve domain parameters shall be generated in a pseudo-random manner using seeds that are generated in a systematic and comprehensive way. The methods by which the parameters have been obtained are explained in Appendix A.
6. Proof of security. For all curves, a proof should be given that all security requirements are met. These proofs are provided in [EBP].

In [BG], attacks are described that apply to elliptic curve domain parameters where $q-1$ has a factor u in the order of $q^{1/3}$. However, the circumstances under which these attacks are applicable can be avoided in most applications. Therefore, no corresponding security requirement is stated here. However, it is highly recommended that developers verify the security of their implementations against this kind of attack.

2.2. Technical Requirements

Commercial demands and experience with existing implementations lead to the following technical requirements for the elliptic curve domain parameters.

1. For each of the bit lengths 160, 192, 224, 256, 320, 384, and 512, one curve shall be proposed. This requirement follows from the need for curves providing different levels of security that are appropriate for the underlying symmetric algorithms. The existing standards specify a 521-bit curve instead of a 512-bit curve.
2. The prime number p shall be congruent 3 mod 4. This requirement allows efficient point compression: one method for the transmission of curve points $P=(x,y)$ is to transmit only x and the least significant bit $\text{LSB}(y)$ of y . For $p = 3 \bmod 4$, we get $(y^2)^{(p+1)/4} = y \cdot y^{(p-1)/2}$, which is either y or $-y$ by Fermat's Little Theorem; hence, y can be computed very efficiently using the curve equation. This requirement is not always met by the parameters defined in existing standards.

3. The curves shall be $\text{GF}(p)$ -isomorphic to a curve E' : $y^2 = x^3 + A'x + B' \bmod p$ with $A' = -3 \bmod p$. This property permits the use of the arithmetical advantages of curves with $A = -3$, as shown by Brier and Joyce [BJ]. For $p = 3 \bmod 4$, approximately half of the isomorphism classes of elliptic curves over $\text{GF}(p)$ contain a curve E' with $A' = -3 \bmod p$. Precisely, if a curve is given by E : $y^2 = x^3 + Ax + B \bmod p$ with $-3 = A \cdot u^4$ being solvable in $\text{GF}(p)$ and $u=Z$ is a solution to this equation, then the requirement is fulfilled by means of the quadratic twist E' : $y^2 = x^3 + Z^4Ax + Z^6B \bmod p$, and the $\text{GF}(p)$ -isomorphism is given by $F(x,y) := (x \cdot Z^2, y \cdot Z^3)$. Due to this isomorphism, $E(\text{GF}(p))$ and $E'(\text{GF}(p))$ have the same number of points, share the same algebraic structure, and hence offer the same level of security. This constraint has also been used by [SEC2] and [FIPS].
4. The prime p must not be of any special form; this requirement is met by a verifiably pseudo-random generation of the parameters (see requirement 5 in Section 2.1). Although parameters specified by existing standards do not meet this requirement, the need for such curves over (pseudo-)randomly chosen fields has already been foreseen by the Standards for Efficient Cryptography Group (SECG), see [SEC2].
5. $\#E(\text{GF}(p)) < p$. As a consequence of the Hasse-Weil Theorem, the number of points $\#E(\text{GF}(p))$ may be greater than the characteristic p of the prime field $\text{GF}(p)$. In some cases, even the bit-length of $\#E(\text{GF}(p))$ can exceed the bit-length of p . To avoid overruns in implementations, we require that $\#E(\text{GF}(p)) < p$. In order to thwart attacks on digital signature schemes, some authors propose to use $q > p$, but the attacks described, e.g., in [BRS], appear infeasible in a well-designed Public Key Infrastructure (PKI).
6. B shall be a non-square mod p . Otherwise, the compressed representations of the curve-points $(0,0)$ and $(0,X)$, with X being the square root of B with a least significant bit of 0, would be identical. As there are implementations of elliptic curves that encode the point at infinity as $(0,0)$, we try to avoid ambiguities. Note that this condition is stable under quadratic twists as described in condition 3 above. Condition 6 makes the attack described in [G] impossible. It can therefore also be seen as a security requirement. This constraint has not been specified by existing standards.

3. Domain Parameter Specification

In this section, the elliptic curve domain parameters proposed are specified in the following way.

For all curves, an ID is given by which it can be referenced.

p is the prime specifying the base field.

A and B are the coefficients of the equation $y^2 = x^3 + Ax + B \pmod{p}$ defining the elliptic curve.

$G = (x, y)$ is the base point, i.e., a point in E of prime order, with x and y being its x - and y -coordinates, respectively.

q is the prime order of the group generated by G .

h is the cofactor of G in E , i.e., $\#E(\mathbb{GF}(p))/q$.

For the twisted curve, we also give the coefficient Z that defines the isomorphism F (see requirement 3 in Section 2.2).

The methods for the generation of the parameters are given in Appendix A. Proofs for the fulfillment of the security requirements specified in Section 2.1 are given in [EBP].

3.1. Domain Parameters for 160-Bit Curves

Curve-ID: brainpoolP160r1

$p = \text{E95E4A5F737059DC60DFC7AD95B3D8139515620F}$

$A = \text{340E7BE2A280EB74E2BE61BADA745D97E8F7C300}$

$B = \text{1E589A8595423412134FAA2DBDEC95C8D8675E58}$

$x = \text{BED5AF16EA3F6A4F62938C4631EB5AF7BDBCDBC3}$

$y = \text{1667CB477A1A8EC338F94741669C976316DA6321}$

$q = \text{E95E4A5F737059DC60DF5991D45029409E60FC09}$

$h = 1$

#Twisted curve

Curve-ID: brainpoolP160t1

Z = 24DBFF5DEC9B986BBFE5295A29BFBAE45E0F5D0B

A = E95E4A5F737059DC60DFC7AD95B3D8139515620C

B = 7A556B6DAE535B7B51ED2C4D7DAA7A0B5C55F380

x = B199B13B9B34EFC1397E64BAEB05ACC265FF2378

y = ADD6718B7C7C1961F0991B842443772152C9E0AD

q = E95E4A5F737059DC60DF5991D45029409E60FC09

h = 1

3.2. Domain Parameters for 192-Bit Curves

Curve-ID: brainpoolP192r1

p = C302F41D932A36CDA7A3463093D18DB78FCE476DE1A86297

A = 6A91174076B1E0E19C39C031FE8685C1CAE040E5C69A28EF

B = 469A28EF7C28CCA3DC721D044F4496BCCA7EF4146FBF25C9

x = C0A0647EAAB6A48753B033C56CB0F0900A2F5C4853375FD6

y = 14B690866ABD5BB88B5F4828C1490002E6773FA2FA299B8F

q = C302F41D932A36CDA7A3462F9E9E916B5BE8F1029AC4ACC1

h = 1

#Twisted curve

Curve-ID: brainpoolP192t1

Z = 1B6F5CC8DB4DC7AF19458A9CB80DC2295E5EB9C3732104CB

A = C302F41D932A36CDA7A3463093D18DB78FCE476DE1A86294

B = 13D56FFAEC78681E68F9DEB43B35BEC2FB68542E27897B79

x = 3AE9E58C82F63C30282E1FE7BBF43FA72C446AF6F4618129

y = 097E2C5667C2223A902AB5CA449D0084B7E5B3DE7CCC01C9

q = C302F41D932A36CDA7A3462F9E9E916B5BE8F1029AC4ACC1

h = 1

3.3. Domain Parameters for 224-Bit Curves

Curve-ID: brainpoolP224r1

p = D7C134AA264366862A18302575D1D787B09F075797DA89F57EC8C0FF

A = 68A5E62CA9CE6C1C299803A6C1530B514E182AD8B0042A59CAD29F43

B = 2580F63CCFE44138870713B1A92369E33E2135D266DBB372386C400B

x = 0D9029AD2C7E5CF4340823B2A87DC68C9E4CE3174C1E6EFDEE12C07D

y = 58AA56F772C0726F24C6B89E4ECDAC24354B9E99CAA3F6D3761402CD

q = D7C134AA264366862A18302575D0FB98D116BC4B6DDEBCA3A5A7939F

h = 1

#Twisted curve

Curve-ID: brainpoolP224t1

Z = 2DF271E14427A346910CF7A2E6CFA7B3F484E5C2CCE1C8B730E28B3F

A = D7C134AA264366862A18302575D1D787B09F075797DA89F57EC8C0FC

B = 4B337D934104CD7BEF271BF60CED1ED20DA14C08B3BB64F18A60888D

x = 6AB1E344CE25FF3896424E7FFE14762ECB49F8928AC0C76029B4D580

y = 0374E9F5143E568CD23F3F4D7C0D4B1E41C8CC0D1C6ABD5F1A46DB4C

q = D7C134AA264366862A18302575D0FB98D116BC4B6DDEBCA3A5A7939F

h = 1

3.4. Domain Parameters for 256-Bit Curves

Curve-ID: brainpoolP256r1

p =
A9FB57DBA1EEA9BC3E660A909D838D726E3BF623D52620282013481D1F6E5377

A =
7D5A0975FC2C3057EEF67530417AFFE7FB8055C126DC5C6CE94A4B44F330B5D9

B =
26DC5C6CE94A4B44F330B5D9BBD77CBF958416295CF7E1CE6BCCDC18FF8C07B6

x =
8BD2AEB9CB7E57CB2C4B482FFC81B7AFB9DE27E1E3BD23C23A4453BD9ACE3262

y =
547EF835C3DAC4FD97F8461A14611DC9C27745132DED8E545C1D54C72F046997

q =
A9FB57DBA1EEA9BC3E660A909D838D718C397AA3B561A6F7901E0E82974856A7

h = 1

#Twisted curve

Curve-ID: brainpoolP256t1

Z =
3E2D4BD9597B58639AE7AA669CAB9837CF5CF20A2C852D10F655668DFC150EF0

A =
A9FB57DBA1EEA9BC3E660A909D838D726E3BF623D52620282013481D1F6E5374

B =
662C61C430D84EA4FE66A7733D0B76B7BF93EBC4AF2F49256AE58101FEE92B04

x =
A3E8EB3CC1CFE7B7732213B23A656149AFA142C47AAFBC2B79A191562E1305F4

y =
2D996C823439C56D7F7B22E14644417E69BCB6DE39D027001DABE8F35B25C9BE

q =
A9FB57DBA1EEA9BC3E660A909D838D718C397AA3B561A6F7901E0E82974856A7

h = 1

3.5. Domain Parameters for 320-Bit Curves

Curve-ID: brainpoolP320r1

p = D35E472036BC4FB7E13C785ED201E065F98FCFA6F6F40DEF4F92B9EC7893EC
28FCD412B1F1B32E27

A = 3EE30B568FBAB0F883CCEBD46D3F3BB8A2A73513F5EB79DA66190EB085FFA9
F492F375A97D860EB4

B = 520883949DFDBC42D3AD198640688A6FE13F41349554B49ACC31DCCD884539
816F5EB4AC8FB1F1A6

x = 43BD7E9AFB53D8B85289BCC48EE5BFE6F20137D10A087EB6E7871E2A10A599
C710AF8D0D39E20611

y = 14FDD05545EC1CC8AB4093247F77275E0743FFED117182EAA9C77877AAAC6A
C7D35245D1692E8EE1

q = D35E472036BC4FB7E13C785ED201E065F98FCFA5B68F12A32D482EC7EE8658
E98691555B44C59311

h = 1

#Twisted curve

Curve-ID: brainpoolP320t1

Z = 15F75CAF668077F7E85B42EB01F0A81FF56ECD6191D55CB82B7D861458A18F
EFC3E5AB7496F3C7B1

A = D35E472036BC4FB7E13C785ED201E065F98FCFA6F6F40DEF4F92B9EC7893EC
28FCD412B1F1B32E24

B = A7F561E038EB1ED560B3D147DB782013064C19F27ED27C6780AAF77FB8A547
CEB5B4FEF422340353

x = 925BE9FB01AFC6FB4D3E7D4990010F813408AB106C4F09CB7EE07868CC136F
FF3357F624A21BED52

y = 63BA3A7A27483EBF6671DBEF7ABB30EBEE084E58A0B077AD42A5A0989D1EE7
1B1B9BC0455FB0D2C3

q = D35E472036BC4FB7E13C785ED201E065F98FCFA5B68F12A32D482EC7EE8658
E98691555B44C59311

h = 1

3.6. Domain Parameters for 384-Bit Curves

Curve-ID: brainpoolP384r1

p = 8CB91E82A3386D280F5D6F7E50E641DF152F7109ED5456B412B1DA197FB711
23ACD3A729901D1A71874700133107EC53

A = 7BC382C63D8C150C3C72080ACE05AFA0C2BEA28E4FB22787139165EFBA91F9
0F8AA5814A503AD4EB04A8C7DD22CE2826

B = 04A8C7DD22CE28268B39B55416F0447C2FB77DE107DCD2A62E880EA53EEB62
D57CB4390295DBC9943AB78696FA504C11

x = 1D1C64F068CF45FFA2A63A81B7C13F6B8847A3E77EF14FE3DB7FCAFE0CBD10
E8E826E03436D646AAEF87B2E247D4AF1E

y = 8ABE1D7520F9C2A45CB1EB8E95CFD55262B70B29FEEC5864E19C054FF99129
280E4646217791811142820341263C5315

q = 8CB91E82A3386D280F5D6F7E50E641DF152F7109ED5456B31F166E6CAC0425
A7CF3AB6AF6B7FC3103B883202E9046565

h = 1

#Twisted curve

Curve-ID: brainpoolP384t1

Z = 41DFE8DD399331F7166A66076734A89CD0D2BCDB7D068E44E1F378F41ECBAE
97D2D63DBC87BCCDDCCC5DA39E8589291C

A = 8CB91E82A3386D280F5D6F7E50E641DF152F7109ED5456B412B1DA197FB711
23ACD3A729901D1A71874700133107EC50

B = 7F519EADA7BDA81BD826DBA647910F8C4B9346ED8CCDC64E4B1ABD11756DCE
1D2074AA263B88805CED70355A33B471EE

x = 18DE98B02DB9A306F2AFCD7235F72A819B80AB12EBD653172476FECD462AAB
FFC4FF191B946A5F54D8D0AA2F418808CC

y = 25AB056962D30651A114AFD2755AD336747F93475B7A1FCA3B88F2B6A208CC
FE469408584DC2B2912675BF5B9E582928

q = 8CB91E82A3386D280F5D6F7E50E641DF152F7109ED5456B31F166E6CAC0425
A7CF3AB6AF6B7FC3103B883202E9046565

h = 1

3.7. Domain Parameters for 512-Bit Curves

Curve-ID: brainpoolP512r1

p = AADD9DB8DBE9C48B3FD4E6AE33C9FC07CB308DB3B3C9D20ED6639CCA703308
717D4D9B009BC66842AECDA12AE6A380E62881FF2F2D82C68528AA6056583A48F3

A = 7830A3318B603B89E2327145AC234CC594CBDD8D3DF91610A83441CAEA9863
BC2DED5D5AA8253AA10A2EF1C98B9AC8B57F1117A72BF2C7B9E7C1AC4D77FC94CA

B = 3DF91610A83441CAEA9863BC2DED5D5AA8253AA10A2EF1C98B9AC8B57F1117
A72BF2C7B9E7C1AC4D77FC94CADC083E67984050B75EBAE5DD2809BD638016F723

x = 81AEE4BDD82ED9645A21322E9C4C6A9385ED9F70B5D916C1B43B62EEF4D009
8EFF3B1F78E2D0D48D50D1687B93B97D5F7C6D5047406A5E688B352209BCB9F822

y = 7DDE385D566332ECC0EABFA9CF7822FDF209F70024A57B1AA000C55B881F81
11B2DCDE494A5F485E5BCA4BD88A2763AED1CA2B2FA8F0540678CD1E0F3AD80892

q = AADD9DB8DBE9C48B3FD4E6AE33C9FC07CB308DB3B3C9D20ED6639CCA703308
70553E5C414CA92619418661197FAC10471DB1D381085DDADDB58796829CA90069

h = 1

#Twisted curve

Curve-ID: brainpoolP512t1

Z = 12EE58E6764838B69782136F0F2D3BA06E27695716054092E60A80BEDB212B
64E585D90BCE13761F85C3F1D2A64E3BE8FEA2220F01EBA5EEB0F35DBD29D922AB

A = AADD9DB8DBE9C48B3FD4E6AE33C9FC07CB308DB3B3C9D20ED6639CCA703308
717D4D9B009BC66842AECDA12AE6A380E62881FF2F2D82C68528AA6056583A48F0

B = 7CBBBCF9441CFAB76E1890E46884EAE321F70C0BCB4981527897504BEC3E36
A62BCDFA2304976540F6450085F2DAE145C22553B465763689180EA2571867423E

x = 640ECE5C12788717B9C1BA06CBC2A6FEBA85842458C56DDE9DB1758D39C031
3D82BA51735CDB3EA499AA77A7D6943A64F7A3F25FE26F06B51BAA2696FA9035DA

y = 5B534BD595F5AF0FA2C892376C84ACE1BB4E3019B71634C01131159CAE03CE
E9D9932184BEEF216BD71DF2DADF86A627306ECFF96DBB8BACE198B61E00F8B332

q = AADD9DB8DBE9C48B3FD4E6AE33C9FC07CB308DB3B3C9D20ED6639CCA703308
70553E5C414CA92619418661197FAC10471DB1D381085DDADDB58796829CA90069

h = 1

4. Object Identifiers and ASN.1 Syntax

4.1. Object Identifiers

The root of the tree for the object identifiers defined in this specification is given by:

```
ecStdCurvesAndGeneration OBJECT IDENTIFIER ::= {iso(1)
  identified-organization(3) teletrust(36) algorithm(3) signature-
  algorithm(3) ecSign(2) 8}
```

The object identifier `ellipticCurve` represents the tree for domain parameter sets. It has the following value:

```
ellipticCurve OBJECT IDENTIFIER ::= {ecStdCurvesAndGeneration 1}
```

The tree containing the object identifiers for each set of domain parameters defined in this RFC is:

```
versionOne OBJECT IDENTIFIER ::= {ellipticCurve 1}
```

The following object identifiers represent the domain parameter sets defined in this RFC:

```
brainpoolP160r1 OBJECT IDENTIFIER ::= {versionOne 1}
brainpoolP160t1 OBJECT IDENTIFIER ::= {versionOne 2}
brainpoolP192r1 OBJECT IDENTIFIER ::= {versionOne 3}
brainpoolP192t1 OBJECT IDENTIFIER ::= {versionOne 4}
brainpoolP224r1 OBJECT IDENTIFIER ::= {versionOne 5}
brainpoolP224t1 OBJECT IDENTIFIER ::= {versionOne 6}
brainpoolP256r1 OBJECT IDENTIFIER ::= {versionOne 7}
brainpoolP256t1 OBJECT IDENTIFIER ::= {versionOne 8}
brainpoolP320r1 OBJECT IDENTIFIER ::= {versionOne 9}
brainpoolP320t1 OBJECT IDENTIFIER ::= {versionOne 10}
brainpoolP384r1 OBJECT IDENTIFIER ::= {versionOne 11}
brainpoolP384t1 OBJECT IDENTIFIER ::= {versionOne 12}
```

brainpoolP512r1 OBJECT IDENTIFIER ::= {versionOne 13}

brainpoolP512t1 OBJECT IDENTIFIER ::= {versionOne 14}

4.2. ASN.1 Syntax for Usage with X.509 Certificates

The domain parameters specified in this RFC SHALL be used with X.509 certificates in accordance with [RFC5480]. In particular,

- o the algorithm field of subjectPublicKeyInfo MUST be set to:
 - * id-ecPublicKey, if the algorithms that can be used with the subject public key are not restricted, or
 - * id-ecDH to restrict the usage of the subject public key to Elliptic Curve Diffie-Hellman (ECDH) key agreement, or
 - * id-ecMQV to restrict the usage of the subject public key to Elliptic Curve Menezes-Qu-Vanstone (ECMQV) key agreement, and
- o the field algorithm.parameter of subjectPublicKeyInfo MUST be of type:
 - * namedCurve to specify the domain parameters by one of the Object Identifiers (OIDs) defined in Section 4.1, or
 - * specifiedCurve to specify the domain parameters explicitly as defined in [RFC5480], or
 - * implicitCurve, if the domain parameters are found in an issuer's certificate.

If the domain parameters are explicitly specified using the type specifiedCurve in the field algorithm.parameter of subjectPublicKeyInfo, ANSI X9.62 [ANSI1] and [RFC5480] allow indicating whether or not a curve and base point have been generated verifiably in a pseudo-random way. Although the parameters specified in Section 3 have all been generated by the pseudo-random methods described in Appendix A, these algorithms deviate from those mandated in ANSI X9.62, A.3.3.1. Consequently, applications following ANSI X9.62 or [RFC5480] will not be able to verify the pseudo-randomness of the parameters. In order to avoid rejection of the parameters, the ASN.1 encoding SHOULD NOT specify that the curve or base point has been generated verifiably at random. In particular, certification authorities (CAs) SHOULD set the contents of specifiedCurve in the following way:

- o version is set to ecvVer1(1).

- o fieldId includes the fieldType prime-field and as parameter the value p of the selected domain parameters as specified in Section 3.
- o curve includes the values a and b of the selected domain parameters as specified in Section 3, but seed is absent.
- o base is the octet string representation of the base point G of the selected domain parameters as specified in Section 3.
- o order is set to q of the selected domain parameters as specified in Section 3.
- o cofactor is set to 1.
- o hash is absent.

5. Security Considerations

The level of security provided by symmetric ciphers and hash functions used in conjunction with the elliptic curve domain parameters specified in this RFC should roughly match or exceed the level provided by the domain parameters. The following table indicates the minimum key sizes for symmetric ciphers and hash functions providing at least (roughly) comparable security.

elliptic curve domain parameters	minimum length of symmetric keys	hash functions
brainpoolP160r1	80	SHA-1, SHA-224, SHA-256, SHA-384, SHA-512
brainpoolP192r1	96	SHA-224, SHA-256, SHA-384, SHA-512
brainpoolP224r1	112	SHA-224, SHA-256, SHA-384, SHA-512
brainpoolP256r1	128	SHA-256, SHA-384, SHA-512
brainpoolP320r1	160	SHA-384, SHA-512
brainpoolP384r1	192	SHA-384, SHA-512
brainpoolP512r1	256	SHA-512

Table 1

Security properties of the elliptic curve domain parameters specified in this RFC are discussed in Section 2.1. Further security discussions specific to elliptic curve cryptography can be found in [ANSI1] and [SEC1].

6. Intellectual Property Rights

The authors have no knowledge about any intellectual property rights that cover the usage of the domain parameters defined herein. However, readers should be aware that implementations based on these domain parameters may require use of inventions covered by patent rights.

7. References

7.1. Normative References

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Appendix A. Pseudo-Random Generation of Parameters

In this appendix, the methods used for pseudo-random generation of the elliptic curve domain parameters are described. A comprehensive description is given in [EBP].

Throughout this section the following conventions are used:

The conversion between integers x in the range $0 \leq x \leq 2^L - 1$ and bit strings of length L is given by $x \leftrightarrow \{x_1, \dots, x_L\}$ and the binary expansion

$x = x_1 * 2^{(L-1)} + x_2 * 2^{(L-2)} + \dots + x_{(L-1)} * 2 + x_L$, i.e., the first bit of the bit string corresponds to the most significant bit of the corresponding integer and the last bit to the least significant bit.

For a real number x , let $\text{floor}(x)$ denote the highest integer less than or equal to x .

For updating the seed s of 160-bit length we use the following function $\text{update_seed}(s)$:

1. Convert s to an integer z .
2. Convert $(z+1) \bmod 2^{160}$ to a bit string t and output t .

A.1. Generation of Prime Numbers

This section describes the systematic selection of the base fields $\text{GF}(p)$ proposed in this specification. The prime generation method is similar to the method given in FIPS 186-2 [FIPS], Appendix 6.4, and ANSI X9.62 [ANSI1], A.3.2. It is a modification of the method "incremental search" given in Section 8.2.2 of [ISO3].

For computing an integer x in the range $0 \leq x \leq 2^L - 1$ from a seed s of 160-bit length, we use the following algorithm $\text{find_integer}(s)$:

1. Set $v = \text{floor}((L-1)/160)$ and $w = L - 160*v$.
2. Compute $h = \text{SHA-1}(s)$.
3. Let h_0 be the bit string obtained by taking the w rightmost bits of h .
4. Convert s to an integer z .
5. For i from 1 to v do:

- A. Set $z_i = (z+i) \bmod 2^{160}$.
 - B. Convert z_i to a bit string s_i .
 - C. Set $h_i = \text{SHA-1}(s_i)$.
6. Let h be the string obtained by the concatenation of h_0, \dots, h_v from left to right.
 7. Convert h to an integer x and output x .

The following procedure is used to generate an L bit prime p from a 160-bit seed s .

1. Set $c = \text{find_integer}(s)$.
2. Let p be the smallest prime $p \geq c$ with $p = 3 \bmod 4$.
3. If $2^{(L-1)} \leq p \leq 2^L - 1$ output p and stop.
4. Set $s = \text{update_seed}(s)$ and go to Step 1.

For the generation of the primes p used as base fields $\text{GF}(p)$ for the curves defined in this specification (and the corresponding twisted curves), the following values (in hexadecimal representation) have been used as initial seed s :

Seed_p_160 for brainpoolP160r1:
3243F6A8885A308D313198A2E03707344A409382

Seed_p_192 for brainpoolP192r1:
2299F31D0082EFA98EC4E6C89452821E638D0137

Seed_p_224 for brainpoolP224r1:
7BE5466CF34E90C6CC0AC29B7C97C50DD3F84D5B

Seed_p_256 for brainpoolP256r1:
5B54709179216D5D98979FB1BD1310BA698DFB5A

Seed_p_320 for brainpoolP320r1:
C2FFD72DBD01ADFB7B8E1AFED6A267E96BA7C904

Seed_p_384 for brainpoolP384r1:
5F12C7F9924A19947B3916CF70801F2E2858EFC1

Seed_p_512 for brainpoolP512r1:
6636920D871574E69A458FEA3F4933D7E0D95748

These seeds have been obtained as the first 7 substrings of 160-bit length each of $Q = \text{Pi} \cdot 2^{1120}$, where Pi is the constant 3.14159..., also known as Ludolph's number, i.e.,

$Q = \text{Seed_p_160} || \text{Seed_p_192} || \dots || \text{Seed_p_512} || \text{Remainder}$,
where $||$ denotes concatenation.

Using these seeds and the above algorithm the following primes are obtained:

$p_{160} = 1332297598440044874827085558802491743757193798159$

$p_{192} = 4781668983906166242955001894344923773259119655253013193367$

$p_{224} = 22721622932454352787552537995910928073340732145944992304435472941311$

$p_{256} = 76884956397045344220809746629001649093037950200943055203735601445031516197751$

$p_{320} = 17635933222391663541619098424460195208895127727195151927729604152886408688021498180955014999035278$

$p_{384} = 21659270770119316173069236842332604979796116387017648600081618503821089934025961822236561982844534088440708417973331$

$p_{512} = 8948962207650232551656602815159153422162609644098354511344597187200057010413552439917934304191956942765446530386427345937963894309923928536070534607816947$

A.2. Generation of Pseudo-Random Curves

The generation procedure is similar to the procedure given in FIPS PUB 186-2 [FIPS], Appendix 6.4, and ANSI X9.62 [ANSI1], A.3.2.

For computing an integer x in the range $0 \leq x \leq 2^{(L-1)} - 1$ from a seed s of 160-bit length, we use the algorithm `find_integer_2(s)`, which slightly differs from the method used for the generation of the primes.

1. Set $v = \text{floor}((L-1)/160)$ and $w = L - 160 \cdot v - 1$.
2. Compute $h = \text{SHA-1}(s)$.
3. Let h_0 be the bit string obtained by taking the w rightmost bits of h .
4. Convert s to an integer z .

5. For i from 1 to v do:
 - A. Set $z_i = (z+i) \bmod 2^{160}$.
 - B. Convert z_i to a bit string s_i .
 - C. Set $h_i = \text{SHA-1}(s_i)$.
6. Let h be the string obtained by the concatenation of h_0, \dots, h_v from left to right.
7. Convert h to an integer x and output x .

The following procedure is used to generate the parameters A and B of a suitable elliptic curve over $\text{GF}(p)$ and a base point G from a prime p of bit length L and a 160-bit seed s .

1. Set $h = \text{find_integer_2}(s)$.
2. Convert h to an integer A .
3. If $-3 = A \cdot Z^4 \bmod p$ is not solvable, then set $s = \text{update_seed}(s)$ and go to Step 1.
4. Compute one solution Z of $-3 = A \cdot Z^4 \bmod p$.
5. Set $s = \text{update_seed}(s)$.
6. Set $B = \text{find_integer_2}(s)$.
7. If B is a square mod p , then set $s = \text{update_seed}(s)$ and go to Step 6.
8. If $4 \cdot A^3 + 27 \cdot B^2 = 0 \bmod p$, then set $s = \text{update_seed}(s)$ and go to Step 1.
9. Check that the elliptic curve E over $\text{GF}(p)$ given by $y^2 = x^3 + A \cdot x + B$ fulfills all security and functional requirements given in Section 3. If not, then set $s = \text{update_seed}(s)$ and go to Step 1.
10. Set $s = \text{update_seed}(s)$.
11. Set $k = \text{find_integer_2}(s)$.
12. Determine the points Q and $-Q$ having the smallest x -coordinate in $E(\text{GF}(p))$. Randomly select one of them as point P .

13. Compute the base point $G = k * P$.

14. Output A, B, and G.

Note: Of course P could also be used as a base point. However, the small x-coordinate of P could possibly render the curve vulnerable to side-channel attacks.

For the generation of curve parameters A and B, and the base points G defined in this specification, the following values (in hexadecimal representation) have been used as initial seed s:

Seed_ab_160 for brainpoolP160r1:
2B7E151628AED2A6ABF7158809CF4F3C762E7160

Seed_ab_192 for brainpoolP192r1:
F38B4DA56A784D9045190CFEF324E7738926CFBE

Seed_ab_224 for brainpoolP224r1:
5F4BF8D8D8C31D763DA06C80ABB1185EB4F7C7B5

Seed_ab_256 for brainpoolP256r1:
757F5958490CFD47D7C19BB42158D9554F7B46BC

Seed_ab_320 for brainpoolP320r1:
ED55C4D79FD5F24D6613C31C3839A2DDF8A9A276

Seed_ab_384 for brainpoolP384r1:
BCFBFA1C877C56284DAB79CD4C2B3293D20E9E5E

Seed_ab_512 for brainpoolP384r1:
AF02AC60ACC93ED874422A52ECB238FEEE5AB6AD

These seeds have been obtained as the first 7 substrings of 160-bit length each of $R = \text{floor}(e * 2^{1120})$, where e denotes the constant 2.71828..., also known as Euler's number, i.e.,

$R = \text{Seed_ab_160} || \text{Seed_ab_192} || \dots || \text{Seed_ab_512} || \text{Remainder}$,
where $||$ denotes concatenation.

Authors' Addresses

Manfred Lochter
Bundesamt fuer Sicherheit in der Informationstechnik (BSI)
Postfach 200363
53133 Bonn
Germany

Phone: +49 228 9582 5643
EMail: manfred.lochter@bsi.bund.de

Johannes Merkle
secunet Security Networks
Mergenthaler Allee 77
65760 Eschborn
Germany

Phone: +49 201 5454 2021
EMail: johannes.merkle@secunet.com

