                Elliptic Curve-Based Certificateless Signatures
                   for Identity-Based Encryption (ECCSI)

Abstract

   Many signature schemes currently in use rely on certificates for
   authentication of identity. In Identity-based cryptography, this
   adds unnecessary overhead and administration. The Elliptic Curve-
   based Certificateless Signatures for Identity-based Encryption
   (ECCSI) signature scheme described in this document is
   certificateless. This scheme has the additional advantages of low
   bandwidth and low computational requirements.

Status of This Memo

   This document is not an Internet Standards Track specification; it is
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1. Introduction

   Digital signatures provide authentication services across a wide
   range of applications. A chain of trust for such signatures is
   usually provided by certificates. However, in low-bandwidth or other
   resource-constrained environments, the use of certificates might be
   undesirable. This document describes an efficient scheme, ECCSI, for
   elliptic curve-based certificateless signatures, primarily intended
   for use with Identity-Based Encryption (IBE) schemes such as
   described in [RFC6508]. As certificates are not needed, the need to
   transmit or store them to authenticate each communication is
   obviated. The algorithm has been developed by drawing on ideas set
   out by Arazi [BA] and is originally based upon the Elliptic Curve
   Digital Signature Algorithm [ECDSA], one of the most commonly used
   signature algorithms.

   The algorithm is for use in the following context:

      * where there are two parties, a Signer and a Verifier;

      * where short unambiguous Identifier strings are naturally
         associated to each of these parties;

   * where a message is to be signed and then verified (e.g., for
      authenticating the initiating party during an Identity-based
      key establishment);

   * where a common Key Management Service (KMS) provides a root of
      trust for both parties.

   The scheme does not rely on any web of trust between users.

   Authentication is provided in a single simplex transmission without
   per-session reference to any third party. Thus, the scheme is
   particularly suitable in situations where the receiving party need
   not be active (or even enrolled) when the message to be authenticated
   is sent, or where the number of transmissions is to be minimized for
   efficiency.

   Instead of having a certificate, the Signer has an Identifier, to
   which his Secret Signing Key (SSK) (see Section 2) will have been
   cryptographically bound by means of a Public Validation Token (PVT)
   (see Section 2) by the KMS. Unlike a traditional public key, this
   PVT requires no further explicit certification.

   The verification primitive within this scheme can be implemented
   using projective representation of elliptic curve points, without
   arithmetic field divisions, and without explicitly using the size of
   the underlying cryptographic group.

1.1. Requirements 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].

2. Architecture

   A KMS provisions key material for a set of communicating devices (a
   "user community"). Each device within the user community MUST have
   an Identifier (ID), which can be formed by its peers. These
   Identifiers MUST be unique to devices (or users), and MAY change over
   time. As such, all applications of this signature scheme MUST define
   an unambiguous format for Identifiers. We consider the situation
   where one device (the Signer) wishes to sign a message that it is
   sending to another (the Verifier). Only the Signer's ID is used in
   the signature scheme.

   In advance, the KMS chooses its KMS Secret Authentication Key (KSAK),
   which is the root of trust for all other key material in the scheme.
   From this, the KMS derives the KMS Public Authentication Key (KPAK),
   which all devices will require in order to verify signatures. This
   will be the root of trust for verification.

   Before verification of any signatures, members of the user community
   are supplied with the KPAK. The supply of the KPAK MUST be
   authenticated by the KMS, and this authentication MUST be verified by
   each member of the user community. Confidentiality protection MAY
   also be applied.

   In the description of the algorithms in this document, it is assumed
   that there is one KMS, one user community, and hence one KPAK.
   Applications MAY support multiple KPAKs, and some KPAKs could in fact
   be "private" to certain communities in certain circumstances. The
   method for determining which KPAK to use (when more than one is
   available) is out of scope.

   The KMS generates and provisions key material for each device. It
   MUST supply an SSK along with a PVT to all devices that are to send
   signed messages. The mechanism by which these SSKs are provided MUST
   be secure, as the security of the authentication provided by ECCSI
   signatures is no stronger than the security of this supply channel.

   Before using the supplied key material (SSK, KPAK) to form
   signatures, the Sender MUST verify the key material (SSK) against the
   root of trust (KPAK) and against its own ID and its PVT, using the
   algorithm defined in Section 5.1.2.

   During the signing process, once the Signer has formed its message,
   it signs the message using its SSK. It transmits the Signature
   (including the PVT), and MAY also transmit the message (in cases
   where the message is not known to the Verifier). The Verifier MUST
   then use the message, Signature, and Sender ID in verification
   against the KPAK.

   This document specifies

      * an algorithm for creating a KPAK from a KSAK, for a given
         elliptic curve;

      * a format for transporting a KPAK;

      * an algorithm for creating an SSK and a PVT from a Signer's ID,
         using the KSAK;

         * an algorithm for verifying an SSK and a PVT against a Signer's
            ID and KPAK;

         * an algorithm for creating a Signature from a message, using a
            Signer's ID with a matching SSK and PVT;

         * a format for transporting a Signature;

         * an algorithm for verifying a Signature for a message, using a
            Signer's ID with the matching KPAK.

   This document does not specify (but comments on)

         * how to choose a valid and secure elliptic curve;

         * which hash function to use;

         * how to format a Signer's ID;

         * how to format a message for signing;

         * how to manage and install a KPAK;

         * how to transport or install an SSK.

   As used in [RFC6509], the elliptic curve and hash function are
   specified in Section 2.1.1 of [RFC6509], the format of Identifiers is
   specified in Section 3.2 of [RFC6509], and messages for signing are
   formatted as specified in [RFC3830].

3. Notation

3.1. Arithmetic

   ECCSI relies on elliptic curve arithmetic. If P and Q are two
   elliptic curve points, their addition is denoted P + Q. Moreover,
   the addition of P with itself k times is denoted [k]P.

   F_p denotes the finite field of p elements, where p is prime. All
   elliptic curve points will be defined over F_p.

   The curve is defined by the equation $y^2 = x^3 - 3*x + B$ modulo p,
   where B is an element of F_p. Elliptic curve points, other than the
   group identity (0), are represented in the format P = (Px,Py), where
   Px and Py are the affine coordinates in F_p satisfying the above
   equation. In particular, a point P = (Px,Py) is said to lie on an
   elliptic curve if $Py^2 - Px^3 + 3*Px - B = 0$ modulo p. The identity
   point 0 will require no representation.

3.2. Representations

   This section provides canonical representations of values that MUST
   be used to ensure interoperability of implementations. The following
   representations MUST be used for input into hash functions and for
   transmission. In this document, concatenation of octet strings s and
   t is denoted s || t. The logarithm base 2 of a real number a is
   denoted lg(a).

   Integers   Integers MUST be represented as an octet string,
                       with bit length a multiple of 8. To achieve this,
                       the integer is represented most significant bit
                       first, and padded with zero bits on the left until
                       an octet string of the necessary length is
                       obtained. This is the octet string representation
                       described in Section 6 of [RFC6090]. There will
                       be no need to represent negative integers. When
                       transmitted or hashed, such octet strings MUST
                       have length N = Ceiling(lg(p)/8).

   F_p elements   Elements of F_p MUST be represented as integers in
                       the range 0 to p-1 using the octet string
                       representation defined above. For use in ECCSI,
                       such octet strings MUST have length N =
                       Ceiling(lg(p)/8).

   Points on E   Elliptic curve points MUST be represented in
                       uncompressed form ("affine coordinates") as
                       defined in Section 2.2 of [RFC5480]. For an
                       elliptic curve point (x,y) with x and y in F_p,
                       this representation is given by 0x04 || x' || y',
                       where x' is the N-octet string representing x and
                       y' is the N-octet string representing y.

3.3. Format of Material

   This section describes the subfields of the different objects used
   within the protocol.

   Signature = r || s || PVT   where r and s are octet strings of length
                               N = Ceiling(lg(p)/8) representing
                               integers, and PVT is an octet string of
                               length 2N+1 representing an elliptic
                               curve point, yielding a total signature
                               length of 4N+1 octets. (Note that r and

                          s represent integers rather than elements
                          of F_p, and therefore it is possible that
                          either or both of them could equal or
                          exceed p.)

4. Parameters

4.1. Static Parameters

   The following static parameters are fixed for each implementation.
   They are not intended to change frequently, and MUST be specified for
   each user community. Note that these parameters MAY be shared across
   multiple KMSs.

      n   A security parameter; the size in bits of the
                          prime p over which elliptic curve cryptography
                          is to be performed.

      N = Ceiling(n/8)   The number of octets used to represent fields r
                          and s in a Signature. Also the number of
                          octets output by the hash function (see below).

      p   A prime number of size n bits. The finite
                          field with p elements is denoted F_p.

      E   An elliptic curve defined over F_p, having a
                          subgroup of prime order q.

      B   An element of F_p, where E is defined by the
                          formula $y^2 = x^3 - 3*x + B$ modulo p.

      G   A point on the elliptic curve E that generates
                          the subgroup of order q.

      q   The prime q is defined to be the order of G in
                          E over F_p.

      Hash   A cryptographic hash function mapping arbitrary
                          strings to strings of N octets. If a, b, c,
                          ... are strings, then hash(a || b || c || ...)
                          denotes the result obtained by hashing the
                          concatenation of these strings.

      Identifiers   The method for deriving user Identifiers. The
                          format of Identifiers MUST be specified by each
                          implementation. It MUST be possible for each
                          device to derive the Identifier for every
                          device with which it needs to communicate. In

                         this document, ID will denote the correctly
                         formatted Identifier string of the Signer.
                         ECCSI makes use of the Signer Identifier only,
                         though an implementation MAY make use of other
                         Identifiers when constructing the message to be
                         signed. Identifier formats MAY include a
                         timestamp to allow for automatic expiration of
                         key material.

   It is RECOMMENDED that p, E, and G are chosen to be standardized
   values. In particular, it is RECOMMENDED that the curves and base
   points defined in [FIPS186-3] be used.

4.2. Community Parameters

   The following community parameter MUST be supplied to devices each
   time the root of trust is changed.

      KPAK The KMS Public Authentication Key (KPAK) is the root of
            trust for authentication. It is derived from the KSAK in
            the KMS. This value MUST be provisioned in a trusted
            fashion, such that each device that receives it has
            assurance that it is the genuine KPAK belonging to its KMS.
            Before use, each device MUST check that the supplied KPAK
            lies on the elliptic curve E.

   The KMS MUST fix the KPAK to be KPAK = [KSAK]G, where the KSAK MUST
   be chosen to be a random secret non-zero integer modulo q. The value
   of the KSAK MUST be kept secret to the KMS.

5. Algorithms

5.1. User Key Material

   To create signatures, each Signer requires a Secret Signing Key (SSK)
   and a Public Validation Token (PVT). The SSK is an integer, and the
   PVT is an elliptic curve point. The SSK MUST be kept secret (to the
   Signer and KMS), but the PVT need not be kept secret. A different
   (SSK,PVT) pair will be needed for each Signer ID.

5.1.1. Algorithm for Constructing (SSK,PVT) Pair

   The KMS constructs a (SSK,PVT) pair from the Signer's ID, the KMS
   secret (KSAK), and the root of trust (KPAK). To do this, the KMS
   MUST perform the following procedure:

1) Choose v, a random (ephemeral) non-zero element of F_q;

2) Compute PVT = [v]G (this MUST be represented canonically -- see
   Section 3.2);

3) Compute a hash value HS = hash(G || KPAK || ID || PVT),
   an N-octet integer;

4) Compute SSK = (KSAK + HS * v) modulo q;

5) If either the SSK or HS is zero modulo q, the KMS MUST erase
   the SSK and abort or restart the procedure with a fresh value
   of v;

6) Output the (SSK,PVT) pair. The KMS MUST then erase the value
   v.

The method for transporting the SSK to the legitimate Signer device
is out of scope for this document, but the SSK MUST be provisioned by
the KMS using a method that protects its confidentiality.

If necessary, the KMS MAY create multiple (SSK,PVT) pairs for the
same Identifier.

5.1.2. Algorithm for Validating a Received SSK

Every SSK MUST be validated before being installed as a signing key.
The Signer uses its ID and the KPAK to validate a received (SSK,PVT)
pair. To do this validation, the Signer MUST perform the following
procedure, passing all checks:

1) Validate that the PVT lies on the elliptic curve E;

2) Compute HS = hash(G || KPAK || ID || PVT), an N-octet
   integer. The integer HS SHOULD be stored with the SSK for
   later use;

3) Validate that KPAK = [SSK]G - [HS]PVT.

5.2. Signatures

5.2.1. Algorithm for Signing

To sign a message (M), the Signer requires

   * the KMS Public Authentication Key, KPAK;

   * the Signer's own Identifier, ID;

      * its Secret Signing Key, SSK;

      * its Public Validation Token, PVT = (PVTx,PVTy).

These values, with the exception of ID, MUST have been provided by the KMS. The value of ID is derived by the Signer using the community-defined method for formatting Identifiers.

The following procedure MUST be used by the Signer to compute the signature:

1) Choose a random (ephemeral) non-zero value j in F_q;

2) Compute J = [j]G (this MUST be represented canonically). Viewing J in affine coordinates J = (Jx,Jy), assign to r the N-octet integer representing Jx;

3) Recall (or recompute) HS, and use it to compute a hash value HE = hash(HS || r || M);

4) Verify that HE + r * SSK is non-zero modulo q; if this check fails, the Signer MUST abort or restart this procedure with a fresh value of j;

5) Compute s' = (((HE + r * SSK)^-1) * j) modulo q; the Signer MUST then erase the value j;

6) If s' is too big to fit within an N-octet integer, then set the N-octet integer s = q - s'; otherwise, set the N-octet integer s = s' (note that since p is less than 2^n, by Hasse's theorem on elliptic curves, $q < 2^n + 2^{(n/2 + 1)} + 1$. Therefore, if $s' > 2^n$, we have $q - s' < 2(n/2 + 1) + 1$. Thus, s is guaranteed to fit within an N-octet integer);

7) Output the signature as Signature = (r || s || PVT).

Note that step 6) is necessary because it is possible for q (and hence for elements of F_q) to be too big to fit within N octets. The Signer MAY instead elect to set s to be the least integer of s' and q - s', represented in N octets.

5.2.2. Algorithm for Verifying

The algorithm provided assumes that the Verifier computes points on elliptic curves using affine coordinates. However, the Verifier MAY perform elliptic curve operations using any appropriate representation of points that achieves the equivalent operations.

To verify a Signature (r || s || PVT) against a Signer's Identifier
(ID), a message (M), and a pre-installed root of trust (KPAK), the
Verifier MUST perform a procedure equivalent to the following:

   1) The Verifier MUST check that the PVT lies on the elliptic
      curve E;

   2) Compute HS = hash(G || KPAK || ID || PVT);

   3) Compute HE = hash(HS || r || M);

   4) Y = [HS]PVT + KPAK;

   5) Compute J = [s]([HE]G + [r]Y);

   6) Viewing J in affine coordinates (Jx,Jy), the Verifier MUST
      check that Jx = r modulo p, and that Jx modulo p is non-zero,
      before accepting the Signature as valid.

It is anticipated that the ID, message (M), and KPAK will be
implicitly understood due to context, but any of these values MAY
also be included in signaling.

Note that the parameter q is not needed during verification.

6. Security Considerations

The ECCSI cryptographic algorithm is based upon [ECDSA]. In fact,
step 5) in the verification algorithm above is the same as the
verification stage in ECDSA. The only difference between ECDSA and
ECCSI is that in ECCSI the 'public key', Y, is derived from the
Signer ID by the Verifier (whereas in ECDSA the public key is fixed).
It is therefore assumed that the security of ECCSI depends entirely
on the secrecy of the secret keys. In addition, to recover secret
keys, one will need to perform computationally intensive
cryptanalytic attacks.

The KSAK provides the security for each device provisioned by the
KMS. It MUST NOT be revealed to any entity other than the KMS that
holds it. Each user's SSK authenticates the user as being associated
with the ID to which the SSK is assigned by the KMS. This key MUST
NOT be revealed to any entity other than the KMS and the authorized
user.

The order of the base point G used in ECCSI MUST be a large prime q.
If k bits of symmetric security are needed, Ceiling(lg(q)) MUST be at
least 2*k.

It is RECOMMENDED that the curves and base points defined in
[FIPS186-3] be used, since these curves are suitable for
cryptographic use. However, if other curves are used, the security
of the curves MUST be assessed.

In order to ensure that the SSK is only received by an authorized
device, it MUST be provided through a secure channel. The strength
of the authentication offered by this signature scheme is no greater
than the security provided by this delivery channel.

Identifiers MUST be defined unambiguously by each application of
ECCSI. Note that it is not necessary to use a hash function to
compose an Identifier string. In this way, any weaknesses that might
otherwise be caused by collisions in hash functions can be avoided
without reliance on the structure of the Identifier format.
Applications of ECCSI MAY include a time/date component in their
Identifier format to ensure that Identifiers (and hence SSKs) are
only valid for a fixed period of time.

The use of the ephemeral value r in the hash HE significantly reduces
the scope for offline attacks, improving the overall security, as
compared to [ECDSA]. Furthermore, if Identifiers are specified to
contain date-stamps, then all Identifiers, SSKs, signatures, and hash
values will periodically become deprecated automatically, reducing
the need for revocation and other additional management methods.

The randomness of values stipulated to be selected at random, as
described in this document, is essential to the security provided by
ECCSI. If the value of the KSAK can be predicted, then any
signatures can be forged. Similarly, if the value of v used by the
KMS to create a user's SSK can be predicted, then the value of the
KSAK could be recovered, which would allow signatures to be forged.
If the value of j used by a user is predictable, then the value of
his SSK could be recovered. This would allow that user's signatures
to be forged. Guidance on the generation of random values for
security can be found in [RFC4086].

Note that in most instances, the value s in the Signature can be
replaced by q - s. Thus, the malleability of ECCSI signatures is
similar to that in [ECDSA]; malleability is available but also very
limited.

7. References

7.1. Normative References

   [ECDSA]   X9.62-2005, "Public Key Cryptography for the Financial
                Services Industry: The Elliptic Curve Digital Signature
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7.2. Informative References

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                contributions/arazi.doc>.

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                (FIPS PUB) 180-3, "Secure Hash Standard (SHS)",
                October 2008.

   [RFC3830]   Arkko, J., Carrara, E., Lindholm, F., Naslund, M., and
                K. Norrman, "MIKEY: Multimedia Internet KEYing",
                RFC 3830, August 2004.

   [RFC4086]   Eastlake 3rd, D., Schiller, J., and S. Crocker,
                "Randomness Requirements for Security", BCP 106,
                RFC 4086, June 2005.

   [RFC6508]   Groves, M., "Sakai-Kasahara Key Encryption (SAKKE)",
                RFC 6508, February 2012.

   [RFC6509]   Groves, M., "MIKEY-SAKKE: Sakai-Kasahara Key Encryption
                in Multimedia Internet KEYing (MIKEY)", RFC 6509,
                February 2012.

Appendix A. Test Data

   This appendix provides test data built from the NIST P-256 curve and
   base point. SHA-256 (as defined in [FIPS180-3]) is used as the hash
   function. The keys and ephemerals -- KSAK, v, and j -- are arbitrary
   and for illustration only.

```
   // ---------------------------------------------------------
   // Global parameters

   n       := 256;

   N       := 32;

   p       := 0x   FFFFFFFF 00000001 00000000 00000000
                   00000000 FFFFFFFF FFFFFFFF FFFFFFFF;

   Hash    := SHA-256;

   // ---------------------------------------------------------
   // Community parameters

   B       := 0x   5AC635D8 AA3A93E7 B3EBBD55 769886BC
                   651D06B0 CC53B0F6 3BCE3C3E 27D2604B;

   q       := 0x   FFFFFFFF 00000000 FFFFFFFF FFFFFFFF
                   BCE6FAAD A7179E84 F3B9CAC2 FC632551;

   G       := 0x   04
                   6B17D1F2 E12C4247 F8BCE6E5 63A440F2
                   77037D81 2DEB33A0 F4A13945 D898C296
                   4FE342E2 FE1A7F9B 8EE7EB4A 7C0F9E16
                   2BCE3357 6B315ECE CBB64068 37BF51F5;

   KSAK    := 0x   12345;

   KPAK    := 0x   04
                   50D4670B DE75244F 28D2838A 0D25558A
                   7A72686D 4522D4C8 273FB644 2AEBFA93
                   DBDD3755 1AFD263B 5DFD617F 3960C65A
                   8C298850 FF99F203 66DCE7D4 367217F4;

   // ---------------------------------------------------------
   // Signer ID

   ID      := "2011-02\0tel:+447700900123\0",
           =  0x   3230 31312D30 32007465 6C3A2B34
                   34373730 30393030 31323300;
```

```
// ---------------------------------------------------------
// Creating SSK and PVT

v        := 0x   23456;

PVT      := 0x   04
                 758A1427 79BE89E8 29E71984 CB40EF75
                 8CC4AD77 5FC5B9A3 E1C8ED52 F6FA36D9
                 A79D2476 92F4EDA3 A6BDAB77 D6AA6474
                 A464AE49 34663C52 65BA7018 BA091F79;

HS       := hash( 0x 04
                 6B17D1F2 E12C4247 F8BCE6E5 63A440F2
                 77037D81 2DEB33A0 F4A13945 D898C296
                 4FE342E2 FE1A7F9B 8EE7EB4A 7C0F9E16
                 2BCE3357 6B315ECE CBB64068 37BF51F5
                 04
                 50D4670B DE75244F 28D2838A 0D25558A
                 7A72686D 4522D4C8 273FB644 2AEBFA93
                 DBDD3755 1AFD263B 5DFD617F 3960C65A
                 8C298850 FF99F203 66DCE7D4 367217F4
                 32303131 2D303200 74656C3A 2B343437

                 37303039 30303132 3300
                 04
                 758A1427 79BE89E8 29E71984 CB40EF75
                 8CC4AD77 5FC5B9A3 E1C8ED52 F6FA36D9
                 A79D2476 92F4EDA3 A6BDAB77 D6AA6474
                 A464AE49 34663C52 65BA7018 BA091F79 ),

          = 0x    490F3FEB BC1C902F 6289723D 7F8CBF79
                  DB889308 49D19F38 F0295B5C 276C14D1;

SSK      := 0x    23F374AE 1F4033F3 E9DBDDAA EF20F4CF
                  0B86BBD5 A138A5AE 9E7E006B 34489A0D;

// ---------------------------------------------------------
// Creating a Signature

M        := "message\0",
           = 0x   6D657373 61676500;

j        := 0x   34567;
```

```
J       := 0x   04
                269D4C8F DEB66A74 E4EF8C0D 5DCC597D
                DFE6029C 2AFFC493 6008CD2C C1045D81
                6DDA6A13 10F4B067 BD5DABDA D741B7CE
                F36457E1 96B1BFA9 7FD5F8FB B3926ADB;

r       := 0x   269D4C8F DEB66A74 E4EF8C0D 5DCC597D
                DFE6029C 2AFFC493 6008CD2C C1045D81;

HE      := hash( 0x
                490F3FEB BC1C902F 6289723D 7F8CBF79
                DB889308 49D19F38 F0295B5C 276C14D1
                269D4C8F DEB66A74 E4EF8C0D 5DCC597D
                DFE6029C 2AFFC493 6008CD2C C1045D81
                6D657373 61676500 ),

         = 0x   111F90EA E8271C96 DF9B3D67 26768D9E
                E9B18145 D7EC152C FA9C23D1 C4F02285;

s'      := 0x   E09B528D 0EF8D6DF 1AA3ECBF 80110CFC
                EC9FC682 52CEBB67 9F413484 6940CCFD;

s       := 0x   E09B528D 0EF8D6DF 1AA3ECBF 80110CFC
                EC9FC682 52CEBB67 9F413484 6940CCFD;

Sig     := 0x   269D4C8F DEB66A74 E4EF8C0D 5DCC597D
                DFE6029C 2AFFC493 6008CD2C C1045D81
                E09B528D 0EF8D6DF 1AA3ECBF 80110CFC
                EC9FC682 52CEBB67 9F413484 6940CCFD
                04

                758A1427 79BE89E8 29E71984 CB40EF75
                8CC4AD77 5FC5B9A3 E1C8ED52 F6FA36D9
                A79D2476 92F4EDA3 A6BDAB77 D6AA6474
                A464AE49 34663C52 65BA7018 BA091F79;

// -------------------------------------------------------
// Verifying a Signature

Y       := 0x   04
                833898D9 39C0013B B0502728 6F95CCE0
                37C11BD2 5799423C 76E48362 A4959978
                95D0473A 1CD6186E E9F0C104 B472499E
                1A24D6CE 3D85173F 02EBBD94 5C25F604;
```

```
     J        := 0x   04
                      269D4C8F DEB66A74 E4EF8C0D 5DCC597D
                      DFE6029C 2AFFC493 6008CD2C C1045D81
                      6DDA6A13 10F4B067 BD5DABDA D741B7CE
                      F36457E1 96B1BFA9 7FD5F8FB B3926ADB;

     Jx       := 0x   269D4C8F DEB66A74 E4EF8C0D 5DCC597D
                      DFE6029C 2AFFC493 6008CD2C C1045D81;

     Jx = r  modulo p

     // ---------------------------------------------------------
```

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