

INTERNATIONAL
STANDARD

ISO/IEC
9796

First edition
1991-09-15

**Information technology — Security
techniques — Digital signature scheme giving
message recovery**

*Technologies de l'information — Techniques de sécurité — Schéma de
signature numérique rétablissant le message*



Reference number
ISO/IEC 9796:1991(E)

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Printed in France

Foreword

ISO (the International Organization for Standardization) and IEC (the International Electrotechnical Commission) form the specialized system for worldwide standardization. National bodies that are members of ISO or IEC participate in the development of International Standards through technical committees established by the respective organization to deal with particular fields of technical activity. ISO and IEC technical committees collaborate in fields of mutual interest. Other international organizations, governmental and non-governmental, in liaison with ISO and IEC, also take part in the work.

In the field of information technology, ISO and IEC have established a joint technical committee, ISO/IEC JTC 1. Draft International Standards adopted by the joint technical committee are circulated to national bodies for voting. Publication as an International Standard requires approval by at least 75 % of the national bodies casting a vote.

International Standard ISO/IEC 9796 was prepared by Joint Technical Committee ISO/IEC JTC 1, *Information technology*.

Annexes A, B, C and D are for information only.

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Introduction

A digital signature in electronic exchange of information is a counterpart to a handwritten signature in classical mail.

Most digital signature schemes are based upon a particular public-key system. Any public-key system includes three basic operations:

- a process producing pairs of keys: a secret key and a public key;
- a process using a secret key;
- a process using a public key.

In any public-key digital signature scheme, the secret key is involved in a signature process for signing messages, and the public key is involved in a verification process for verifying signatures. A pair of keys for a digital signature scheme thus consists of a "secret signature key" and a "public verification key".

Two types of digital signature schemes are clearly identified.

- When the verification process needs the message as part of the input, the scheme is named a "signature scheme with appendix". The use of a hash-function is involved in the calculation of the appendix.
- When the verification process reveals the message together with its specific redundancy (sometimes called the "shadow of a message"), the scheme is named a "signature scheme giving message recovery".

This International Standard specifies a scheme for digital signature of messages of limited length.

This digital signature scheme allows a minimal resource requirement for verification. It does not involve the use of a hash-function and it avoids the known attacks against the generic algorithm in use.

The message need not be in a natural language. It may be any arbitrary string of bits of limited length. Examples of such messages are cryptographic key materials and the result of hashing another, longer message, which is also called the "imprint of a message". A characteristic example is a structured set of a few strings of bits generated by cryptographic software and hardware, one of these strings coding control information produced within the hardware.

NOTE — The use of this International Standard may involve patented items.

Information technology — Security techniques — Digital signature scheme giving message recovery

1 Scope

This International Standard specifies a digital signature scheme giving message recovery for messages of limited length and using a public-key system.

This digital signature scheme includes

- a signature process using a secret signature key and a signature function for signing messages;
- a verification process using a public verification key and a verification function for checking signatures while recovering messages.

During the signature process, messages to be signed are padded and extended if necessary. Artificial redundancy is then added, depending upon the message itself. No assumption is made as to the possible presence of natural redundancy in the messages. The artificial redundancy is revealed by the verification process. The removal of this artificial redundancy gives message recovery.

This International Standard does not specify the key production process, the signature function and the verification function. Annex A gives an example of a public-key system including key production, signature function and verification function. The various steps of these operations are illustrated by examples in annex B.

Some parameters in the scheme are related to security: this International Standard does not specify the values to be used in order to reach a given level of security. However, this International Standard is specified in such a way as to minimize the required changes in its use if some of these parameters have to be modified.

2 Definitions

For the purposes of this International Standard, the following definitions apply.

2.1 message: String of bits of limited length.

2.2 signature: String of bits resulting from the signature process.

3 Symbols and abbreviations

<i>MP</i>	Padded message
<i>ME</i>	Extended message
<i>MR</i>	Extended message with redundancy
<i>IR</i>	Intermediate integer
Σ	Signature
k_s	Length of the signature in bits
<i>IR'</i>	Recovered intermediate integer
<i>MR'</i>	Recovered message with redundancy
<i>MP'</i>	Recovered padded message
Sign	Signature function under control of the secret signature key
Verif	Verification function under control of the public verification key
mod <i>z</i>	Arithmetic computation modulo <i>z</i>
μ	Nibble
Π	Permutation of the nibbles
<i>m</i>	Byte
<i>S</i>	Shadow of the bytes
$X \parallel Y$	Concatenation of strings of bits <i>X</i> and <i>Y</i>
$X \oplus Y$	Exclusive-or of strings of bits <i>X</i> and <i>Y</i>

NOTES

1 All integers (and all strings of bits or bytes) are written with the most significant digit (or bit or byte) in left position.

2 The hexadecimal notation, with the digits 0 to 9 and A to F, is used in table 1 and in annex B.

4 General overview

The next two clauses specify

- the signature process in clause 5;
- the verification process in clause 6.

Each signing entity shall use and keep secret its own signature key corresponding to its own public verification key.

Messages to be signed shall be padded and extended if necessary. Redundancy is then added according to rules specified in clause 5. From the extended messages with redundancy, signatures shall be computed using the secret signature key as specified in clause 5.

Each verifying entity should know and use the public verification key specific to the signing entity. A signature shall be accepted if and only if the verification process specified in clause 6 is successful.

NOTE — The production and the distribution of keys fall outside the scope of this International Standard.

5 Signature process

Figure 1 summarizes the signature process.

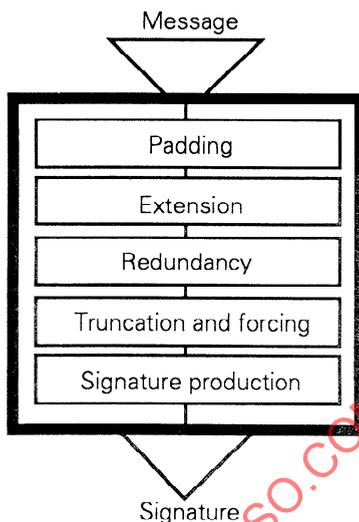


Figure 1 — Signature process

NOTE — A good implementation of the signature process should physically protect the operations in such a way that there is no direct access to the signature function under control of the secret signature key.

5.1 Padding

The message is a string of bits. This string of bits is padded to the left by 0 to 7 zeroes so as to obtain a string of z bytes. Index r , to be used later on, is the number of padded zeroes plus one. Index r is thus valued from 1 to 8.

Consequently, in the padded message denoted by MP , the $8z+1-r$ least significant bits are information bearing.

$$MP = m_z \parallel m_{z-1} \parallel \dots \parallel m_2 \parallel m_1$$

$$m_z = (r-1 \text{ padded zeroes}) \parallel (9-r \text{ information bits})$$

Number z multiplied by sixteen shall be less than or equal to number k_s+3 . Consequently, the number of bits of the message to be signed shall be at most 8 times the largest integer less than or equal to $(k_s+3)/16$.

5.2 Extension

Number t , to be used later on, is the least integer such that a string of $2t$ bytes includes at least k_s-1 bits.

The extended message ME is obtained by repeating the z bytes of MP , as many times as necessary, in order and concatenated to the left, until forming a string of t bytes.

For i valued from 1 to t and j equal to $i-1 \pmod{z}$ plus one (j is therefore valued from 1 to z), the i -th byte of ME equals the j -th byte of MP .

$$ME = \dots m_z \parallel \dots m_2 \parallel m_1$$

← t bytes →

NOTE — Number z is less than or equal to number t . The equality may occur only if k_s is congruent to 13, 14, 15, 0 or 1 mod 16.

5.3 Redundancy

The extended message with redundancy MR is obtained by interleaving the t bytes of ME in odd positions and t bytes of redundancy in even positions. Altered by index r , the least significant nibble of the $2z$ -th byte of MR codes the message length by its value and its position.

For i valued from 1 to t ,

- the $(2i-1)$ -th byte of MR equals the i -th byte of ME ;
- the $2i$ -th byte of MR equals the image of the i -th byte of ME according to the shadow S specified in table 1, except for the $2z$ -th byte of MR which equals the exclusive or of index r with the shadow of the z -th byte of ME .

$$MR = \dots S(m_z) \oplus r \parallel m_z \parallel \dots S(m_2) \parallel m_2 \parallel S(m_1) \parallel m_1$$

← $2t$ bytes →

NOTE — The computation of the $2t$ bytes of MR (mr_{2t} to mr_1) from the z bytes of MP (mp_z to mp_1) is performed by applying successively the following three formulae for i valued from 1 to t .

$$j := (i-1 \pmod{z}) + 1; \quad mr_{2i-1} := mp_j; \quad mr_{2i} := S(mp_j)$$

Finally, the $2z$ -th byte is altered by index r .

$$mr_{2z} := r \oplus mr_{2z}$$

5.4 Truncation and forcing

The intermediate integer IR is coded by a string of k_s bits where the most significant bit is valued to 1 and where the k_s-1 least significant bits are those of MR , except for the least significant byte which is replaced. If $\mu_2 \parallel \mu_1$ is the least significant byte of MR , then the least significant byte of IR shall be $\mu_1 \parallel 6$.

5.5 Signature production

The signature Σ is obtained as a string of k_s bits by applying to IR the signature function under control of the secret signature key.

$$\Sigma = \text{Sign}(IR)$$

Table 1 — Permutation Π and shadow S

μ	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
$\Pi(\mu)$	E	3	5	8	9	4	2	F	0	D	B	6	7	A	C	1

If nibble μ consists of the bits $a_4 a_3 a_2 a_1$, then under the permutation Π , its image denoted by $\Pi(\mu)$ consists of the bits $a_4 \oplus a_2 \oplus a_1 \oplus 1$; $a_4 \oplus a_3 \oplus a_1 \oplus 1$; $a_4 \oplus a_3 \oplus a_2 \oplus 1$; $a_3 \oplus a_2 \oplus a_1$.

If byte m consists of the nibbles $\mu_2 \mu_1$, then under the shadow S , its image denoted by $S(m)$ consists of the nibbles $\Pi(\mu_2) \Pi(\mu_1)$.

6 Verification process

Figure 2 summarizes the verification process.

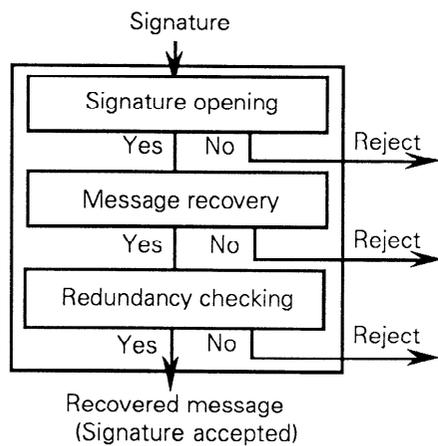


Figure 2 — Verification process

6.1 Signature opening

The signature Σ is transformed into the recovered intermediate integer IR' by applying to Σ the verification function under control of the public verification key.

$$IR' = \text{Verif}(\Sigma)$$

The signature Σ shall be rejected if IR' is not a string of k_s bits where the most significant bit is valued to 1 and where the least significant nibble is valued to 6.

6.2 Message recovery

The recovered message with redundancy MR' is the string of $2t$ bytes where the $1-k_s \pmod{16}$ most significant bits are null and where the k_s-1 least significant bits are those of IR' , except for the least significant byte which is replaced. According to the permutation Π

specified in table 1, if $\mu_4 \parallel \mu_3 \parallel \mu_2 \parallel \mu_1$ are the four least significant nibbles of IR' , then the least significant byte of MR' shall be $\Pi^{-1}(\mu_4) \parallel \mu_2$.

$$MR' = m_{2t} \parallel m_{2t-1} \parallel \dots \parallel m_2 \parallel m_1$$

NOTE — The strings MR and MR' may be unequal. The string MR' consists of the k_s-1 least significant bits of MR padded by 0 to 15 zeroes in the most significant bits.

From the $2t$ bytes of MR' , t sums are computed. According to the shadow S specified in table 1, the i -th sum equals the exclusive-or of the $2i$ -th byte with the shadow of the $(2i-1)$ -th byte.

$$m_{2i} \oplus S(m_{2i-1})$$

The signature Σ shall be rejected if the t sums are null.

Number z is recovered as the position of the first non-null sum. The recovered padded message MP' is the string of the z least significant bytes in odd positions in MR' .

$$MP' = m_{2z-1} \parallel m_{2z-3} \parallel \dots \parallel m_{2i-1} \parallel \dots \parallel m_3 \parallel m_1$$

Index r is recovered as the value of the least significant nibble of the first non-null sum.

The signature Σ shall be rejected if index r is not valued from 1 to 8, and also if the $r-1$ most significant bits of MP' are not all null.

$$m_{2z-1} = (r-1 \text{ padded zeroes}) \parallel (9-r \text{ information bits})$$

The message is recovered as the string of the $8z+1-r$ least significant bits of MP' .

6.3 Redundancy checking

The signature Σ shall be accepted if and only if the k_s-1 least significant bits of MR' are equal to the k_s-1 least significant bits of another extended message with redundancy computed from the recovered padded message MP' according to 5.2 and 5.3.

Annex A (informative)

Example of a public-key system for digital signature

A.1 Definitions

Modulus: Integer constructed as the product of two primes.

Public verification key: Modulus and verification exponent.

Secret signature key: Signature exponent.

A.2 Symbols and abbreviations

RR	Representative element
IS	Resulting integer
n	Modulus
k	Length of the modulus in bits
p, q	Prime factors of the modulus
v	Verification exponent
s	Signature exponent
$\text{lcm}(a, b)$	Least common multiple of integers a and b
$(a n)$	Jacobi symbol of a with respect to n

NOTE — Let p be an odd prime, and let a be a positive integer. The Legendre symbol of integer a with respect to prime p is defined by the following formula.

$$(a | p) = a^{(p-1)/2} \pmod{p}$$

When integer a is not a multiple of p , then the Legendre symbol of integer a with respect to prime p is valued to either +1 or -1 depending on whether integer a is or is not a square modulo p .

The Legendre symbol of multiples of p with respect to prime p is null.

Let n be an odd positive integer, and let a be a positive integer. The Jacobi symbol of integer a with respect to integer n is the product of the Legendre symbols of integer a with respect to the prime factors of n .

Therefore if $n = p q$, then $(a | n) = (a | p) (a | q)$.

The Jacobi symbol of any integer a with respect to any integer n may be efficiently computed without the prime factors of n .

A.3 Key production

A.3.1 Public verification exponent

Each signing entity shall select a positive integer v as its public verification exponent.

The public verification exponent may be standardized in specific applications.

NOTE — Values 2 and 3 may have some practical advantages.

A.3.2 Secret prime factors and public modulus

Each signing entity shall secretly and randomly select two distinct odd primes p and q subject to the following conditions.

— If v is odd, then $p-1$ and $q-1$ shall be coprime to v .

— If v is even, then $(p-1)/2$ and $(q-1)/2$ shall be coprime to v . Moreover, p and q shall not be congruent to each other mod 8.

The public modulus n is the product of the secret prime factors p and q .

$$n = p q$$

The length of the modulus is k . Number k shall equal k_s+1 .

NOTES

1 Some additional conditions on the choice of primes may well be taken into account in order to deter factorization of the modulus.

2 Some forms of the modulus simplify the modulo reduction and need less table storage. These forms are

$$F_{x, y, -} : n = 2^{64x} - c \quad \text{of length : } k = 64x \text{ bits,}$$

$$F_{x, y, +} : n = 2^{64x} + c \quad \text{of length : } k = 64x + 1 \text{ bits,}$$

$$\text{where : } 1 \leq y \leq 2x \text{ and } c < 2^{64x-8y} < 2c.$$

In the negative forms, all the bits of the y most significant bytes are valued to one, up to a quarter of the length of the modulus.

In the positive forms, after a single most significant bit valued to one, all the bits of the y most significant bytes are valued to zero, up to a quarter of the length of the modulus.

A.3.3 Secret signature exponent

The secret signature exponent is the least positive integer s such that $sv-1$ is a multiple of

— $\text{lcm}(p-1, q-1)$ if v is odd;

— $\frac{1}{2} \text{lcm}(p-1, q-1)$ if v is even.

A.4 Signature function

The intermediate integer IR is a string of $k-1$ bits computed as described in 5.4.

The representative element of IR with respect to n is denoted by RR .

- If v is odd, then RR is IR .
- If v is even and if $(IR \mid n) = +1$, then RR is IR .
- If v is even and if $(IR \mid n) = -1$, then RR is $IR/2$.

NOTE — If v is even, then the Jacobi symbol of RR with respect to n is forced to $+1$.

RR shall be raised to the power s modulo n . The signature Σ is either the result or its complement to n , the least one.

$$\Sigma = \min \{ RR^s \bmod n, n - (RR^s \bmod n) \}$$

This defines the signature function "Sign".

$$\Sigma = \text{Sign}(IR)$$

A.5 Verification function

The signature Σ is a positive integer less than $n/2$ which shall be raised to the power v modulo n for obtaining the resulting integer IS .

The recovered intermediate integer IR' is then defined by the following decoding.

- If IS is congruent to $6 \bmod 16$, then IR' is IS .
- If $n-IS$ is congruent to $6 \bmod 16$, then IR' is $n-IS$.

Moreover, when v is even,

- if IS is congruent to $3 \bmod 8$, then IR' is $2IS$;
- if $n-IS$ is congruent to $3 \bmod 8$, then IR' is $2(n-IS)$.

The signature Σ shall be rejected in all the other cases, and also if IR' does not lie in the range from 2^{k-2} to $2^{k-1}-1$.

This defines the verification function "Verif".

$$IR' = \text{Verif}(\Sigma)$$

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Annex B (informative)

Illustrative examples related to annex A

The hexadecimal notation is used.

B.1 Examples with public exponent three

B.1.1 Key production

The public verification exponent v is 3.

Therefore the secret prime factors are both congruent to 2 mod 3.

$p =$	BA09106C 754EB6FE BBC21479 9FF1B8DE 1B4CBB7A 7A782B15 7C1BC152 90A1A3AB
$q =$	1 6046EB39 E03BEAB6 21D03C08 B8AE6B66 CFF955B6 4B4F48B7 EE152A32 6BF8CB25

The public modulus n of 513 bits is of the form $2^{512} + c$
with $2c > 2^{384} > c$ (form $F_x, y, +$ with $x = 8$ and $y = 16$).

$n = p q =$	1 00000000 00000000 00000000 00000000 BBA2D15D BB303C8A 21C5EBBC BAE52B71 25087920 DD7CDF35 8EA119FD 66FB0640 12EC8CE6 92F0A0B8 E8321B04 1ACD40B7
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The secret signature exponent s is $(n-p-q+3)/6$.

$s =$	2AAAAAAAA AAAAAAAAA AAAAAAAAA AAAAAAAAA C9F0783A 49DD5F6C 5AF651F4 C9D0DC92 81C96A3F 16A85F95 72D7CC3F 2D0F25A9 DBF1149E 4CDC3227 3FAADD3F DA5DCA7
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B.1.2 Length of the variables

Number z is a positive integer less than or equal to $k+2$ divided by 16. Number t is the largest integer less than or equal to $k+13$ divided by 16.

Consequently, when number k is 513,

— number z is valued from 1 to 32, the messages to be signed are strings of 1 to 256 bits, and the padded messages MP and MP' are strings of 1 to 32 bytes;

— number t is 32, the extended messages ME are strings of 32 bytes, and the messages with redundancy MR and MR' are strings of 64 bytes.

Moreover, the intermediate integers IR and IR' and the signatures Σ are strings of 512 bits ($k-1$ bits).

B.1.3 Example 1

This example illustrates padding, extension and truncation for signing a message of 100 bits.

C BBAA 9988 7766 5544 3322 1100

Signature process

After padding four zeroes to the left, the padded message MP is a string of 13 bytes. Therefore $z=13$ and $r=5$.

$MP =$ 0C BBAA9988 77665544 33221100

The extended message ME results by repeating the 13 successive bytes of MP , in order and concatenated to the left, until obtaining a string of 32 bytes.

$ME =$ 55443322 11000CBB AA998877 66554433
2211000C BBAA9988 77665544 33221100

The extended message with redundancy MR is a string of 64 bytes obtained by interleaving the 32 bytes of ME and 32 bytes of redundancy. An alteration of the 26-th byte (E2) codes the message border.

$MR =$ 44559944 88335522 3311EE00 E70C66BB
BBAADD99 0088FF77 22664455 99448833
55223311 EE00E20C 66BBBBAA DD990088
FF772266 44559944 88335522 3311EE00

The intermediate integer IR results from MR by truncating to 511 bits, by padding to the left one bit valued to 1 and by replacing the least significant byte: $\mu_2 \parallel \mu_1 = 00$ is replaced by $\mu_1 \parallel 6 = 06$.

Because v is odd, the representative element RR is IR .

$RR = IR =$ C4559944 88335522 3311EE00 E70C66BB
BBAADD99 0088FF77 22664455 99448833
55223311 EE00E20C 66BBBBAA DD990088
FF772266 44559944 88335522 3311EE06

RR is raised to the power s modulo n . The signature Σ is here the complement to n of the result.

$\Sigma =$ 309F873D 8DED8379 490F6097 EAAFDABC
137D3EBF D8F25AB5 F138D56A 719CDC52
6BDD022E A65DABAB 920A8101 3A85D092
E04D3E42 1CAAB717 C90D89EA 45A8D23A

Verification process

The signature Σ is less than $n/2$. The resulting integer IS is obtained by raising Σ to the power 3 modulo n .

$IS =$ 3BAA66BB 77CCAADD CCEE11FF 18F39944
 FFF7F3C4 BAA73D12 FF5FA767 21A0A33D
 CFE6460E EF7BFD29 27E55E52 896205B7
 13756A80 4E9B0774 5FFEC5E1 E7B52B1

The intermediate integers are strings of 512 bits where the most significant bit is valued to 1 and the least significant nibble is valued to 6. Because n is here congruent to 7 mod 16 and IS to 1 mod 16, the recovered intermediate integer IR' is $n-IS$.

$IR' = n-IS =$ C4559944 88335522 3311EE00 E70C66BB
 BBAADD99 0088FF77 22664455 99448833
 55223311 EE00E20C 66BBBBAA DD990088
 FF772266 44559944 88335522 3311EE06

The recovered message with redundancy MR' is here the string of 64 bytes where a padded zero is followed by the 511 least significant bits of IR' , except for the least significant byte; according to the permutation Π stating $\Pi(0) = E$, EE06 denoted by $\mu_4 \parallel \mu_3 \parallel \mu_2 \parallel \mu_1$ is replaced by $\mu_4 \parallel \mu_3 \parallel \Pi^{-1}(\mu_4) \parallel \mu_2$ valued to EE00.

$MR' =$ 44559944 88335522 3311EE00 E70C66BB
 BBAADD99 0088FF77 22664455 99448833
 55223311 EE00E20C 66BBBBAA DD990088
 FF772266 44559944 88335522 3311EE00

The first non-null sum is the 13-th sum valued to 5. Thus $z=13$ and $r=5$. The recovered padded message MP' is the string of the 13 bytes of MR' in the least significant odd positions.

$MP' =$ 0C BBAA9988 77665544 33221100

The four most significant bits ($r-1=4$) of MP' are null. The message itself is recovered as the string of the least significant 100 bits ($8z+1-r=100$) of MP' .

C BBAA 9988 7766 5544 3322 1100

The signature is accepted because the 511 least significant bits of the recovered message with redundancy MR' are recovered in the extended message with redundancy computed from MP' , exactly as MR from MP .

B.1.4 Example 2

This example illustrates a simpler case: a 256-bit message is neither padded nor extended with a 513-bit modulus.

FEDC BA98 7654 3210 FEDC BA98 7654 3210
 FEDC BA98 7654 3210 FEDC BA98 7654 3210

Signature process

The message is a string of 256 bits, coded over exactly 32 bytes. Therefore z is 32 and r is 1. The message equals the padded message MP and the extended message ME .

$ME = MP =$ FEDCBA98 76543210 FEDCBA98 76543210
 FEDCBA98 76543210 FEDCBA98 76543210

The extended message with redundancy MR is a string of 64 bytes.

$MR =$ 1DFEA7DC 6BBAD098 F2764954 85323E10
 1CFEA7DC 6BBAD098 F2764954 85323E10
 1CFEA7DC 6BBAD098 F2764954 85323E10
 1CFEA7DC 6BBAD098 F2764954 85323E10

The intermediate integer IR results from MR by truncating to 511 bits, by padding to the left one bit valued to 1 and by replacing the least significant byte.

Because v is odd, the representative element RR is IR .

$RR = IR =$ 9DFEA7DC 6BBAD098 F2764954 85323E10
 1CFEA7DC 6BBAD098 F2764954 85323E10
 1CFEA7DC 6BBAD098 F2764954 85323E10
 1CFEA7DC 6BBAD098 F2764954 85323E06

RR is raised to the power s modulo n . The signature Σ is here the result.

$\Sigma =$ 319BB9BE CB49F3ED 1BCA26D0 FCF09B0B
 0A508E4D 0BD43B35 0F959B72 CD25B3AF
 47D608FD CD248EAD A74FBE19 990DBEB9
 BF0DA4B4 E1200243 A14E5CAB 3F7E610C

Verification process

The signature Σ is less than $n/2$. The resulting integer IS is obtained by raising Σ to the power 3 modulo n .

Because IS is here congruent to 1 mod 16, the recovered intermediate integer IR' is here IS .

$IR' = IS =$ 9DFEA7DC 6BBAD098 F2764954 85323E10
 1CFEA7DC 6BBAD098 F2764954 85323E10
 1CFEA7DC 6BBAD098 F2764954 85323E10
 1CFEA7DC 6BBAD098 F2764954 85323E06

The recovered message with redundancy MR' is here the string of 64 bytes where a padded zero is followed by the 511 least significant bits of IR' , except for the least significant byte; according to the permutation Π stating $\Pi(1) = 3$, 3E06 denoted by $\mu_4 \parallel \mu_3 \parallel \mu_2 \parallel \mu_1$ is replaced by $\mu_4 \parallel \mu_3 \parallel \Pi^{-1}(\mu_4) \parallel \mu_2$ valued to 3E10.

$MR' =$ 1DFEA7DC 6BBAD098 F2764954 85323E10
 1CFEA7DC 6BBAD098 F2764954 85323E10
 1CFEA7DC 6BBAD098 F2764954 85323E10
 1CFEA7DC 6BBAD098 F2764954 85323E10

The first non-null sum is the 32-nd sum valued to 1. Thus $z=32$ and $r=1$. The recovered padded message MP' is the string of the 32 bytes of MR' in odd positions.

$MP' =$ FEDCBA98 76543210 FEDCBA98 76543210
 FEDCBA98 76543210 FEDCBA98 76543210

The recovered message is a string of 256 bits.

FEDC BA98 7654 3210 FEDC BA98 7654 3210
 FEDC BA98 7654 3210 FEDC BA98 7654 3210

The signature is accepted because the 511 least significant bits of the recovered message with redundancy MR' are recovered in the extended message with redundancy computed from MP' , exactly as MR from MP .

B.2 Another example with public exponent three

B.2.1 Key production

The public verification exponent v is 3.

Therefore the secret prime factors are both congruent to 2 mod 3.

$p =$ 461908C5 405B7952 F69864C3 B0683002
 5650303D 5297A4BD 2F549A9D 37CFE027
 $q =$ 3 A6EC260F 3E2E0B2C 106C5164 6D471D9E
 04783176 27010818 E54CC26F 7C0C892B

The public modulus n of 512 bits is of the form $2^{512} - c$,
 with $2c > 2^{488} > c$ (form $F_x, y, -$ with $x = 8$ and $y = 3$).

$n = p q =$ FFFFFFFF7F A27087C3 5EBEAD78 412D2BDF
 FE0301ED D494DF13 458974EA 89B36470
 8F7D0F5A 00A50779 DDF9F7D4 CB80B889
 1324DA25 1A860C4E C9EF2881 04B3858D

The secret signature exponent s is $(n-p-q+3)/6$.

$s =$ 2AAAAA95 45BD6BF5 E51FC794 0ADCDA5
 55008052 4E18CFD8 8B96E8D1 C19DE612
 1B13FAC0 EB0495D4 7928E047 724D91D1
 740F6968 457CE53E C8E24C93 62CE84B5

B.2.2 Length of the variables

Because number k is 512,

- number z is valued from 1 to 32, the messages to be signed are strings of 1 to 256 bits, and the padded messages MP and MP' are strings of 1 to 32 bytes;
- number t is 32, the extended messages ME are strings of 32 bytes, and the messages with redundancy MR and MR' are strings of 64 bytes.

Moreover, the intermediate integers IR and IR' and the signatures Σ are strings of 511 bits ($k-1$ bits).

B.2.3 Example 3

This example illustrates padding, extension and truncation for signing a message of 100 bits.

1 1223 3445 5667 7889 9AAB BCCD

Signature process

After padding four zeroes to the left, the padded message MP is a string of 13 bytes. Therefore $z=13$ and $r=5$.

$MP =$ 01 12233445 56677889 9AABBCCD

The extended message ME results by repeating the 13 successive bytes of MP , in order and concatenated to the left, until obtaining a string of 32 bytes.

$ME =$ 78899AAB BCCD0112 23344556 6778899A
 ABBCCD01 12233445 56677889 9AABBCCD

The extended message with redundancy MR is a string of 64 bytes obtained by interleaving the 32 bytes of ME and 32 bytes of redundancy. An alteration of the 26-th byte (E6) codes the message border.

$MR =$ F0780D89 DB9AB6AB 67BC7ACD E3013512
 58238934 94454256 2F67F078 0D89DB9A
 B6AB67BC 7ACDE601 35125823 89349445
 42562F67 F0780D89 DB9AB6AB 67BC7ACD

The intermediate integer IR results from MR by truncating to 510 bits, by padding to the left one bit valued to 1 and by replacing the least significant byte: $\mu_2 \parallel \mu_1 = CD$ is replaced by $\mu_1 \parallel 6 = D6$.

Because v is odd, the representative element RR is IR .

$RR = IR =$ 70780D89 DB9AB6AB 67BC7ACD E3013512
 58238934 94454256 2F67F078 0D89DB9A
 B6AB67BC 7ACDE601 35125823 89349445
 42562F67 F0780D89 DB9AB6AB 67BC7AD6

RR is raised to the power s modulo n . The signature Σ is here the complement to n of the result.

$\Sigma =$ 58E59FFB 4B1FB1BC DBF8D1FE 9AFA3730
 C78A318A 1134F579 1B7313D4 80FF07AC
 319B068E DF8F2129 45CB09CF 33DF30AC
 E54F4A06 3FCCA0B7 32F4B662 DC4E2454

Verification process

The signature Σ is less than $n/2$. The resulting integer IS is obtained by raising Σ to the power 3 modulo n .

$IS =$ 8F87F1F5 C6D5D117 F70232AA 5E2BF6CD
 A5DF78B9 404F9CBD 16218472 7C2988D5
 D8D1A79D 85D72178 A8E79FB1 424C2443
 D0CEAABD 2A0DFEC4 EE5471D5 9CF70AB7

The intermediate integers are strings of 511 bits where the most significant bit is valued to 1 and the least significant nibble is valued to 6. Because n is here congruent to 13 mod 16 and IS to 7 mod 16, the recovered intermediate integer IR' is $n-IS$.

$IR' = n-IS =$ 70780D89 DB9AB6AB 67BC7ACD E3013512
 58238934 94454256 2F67F078 0D89DB9A
 B6AB67BC 7ACDE601 35125823 89349445
 42562F67 F0780D89 DB9AB6AB 67BC7AD6

The recovered message with redundancy MR' is here the string of 64 bytes where two padded zeroes are followed by the 510 least significant bits of IR' , except for the least significant byte; according to the permutation Π stating $\Pi(C) = 7$, 7AD6 denoted by $\mu_4 \parallel \mu_3 \parallel \mu_2 \parallel 6$ is replaced by $\mu_4 \parallel \mu_3 \parallel \Pi^{-1}(\mu_4) \parallel \mu_2$ valued to 7ACD.

$MR' =$ 30780D89 DB9AB6AB 67BC7ACD E3013512
 58238934 94454256 2F67F078 0D89DB9A
 B6AB67BC 7ACDE601 35125823 89349445
 42562F67 F0780D89 DB9AB6AB 67BC7ACD

The first non-null sum is the 13-th sum valued to 5. Thus $z=13$ and $r=5$. The recovered padded message MP' is the string of the 13 bytes of MR' in the least significant odd positions.

$MP' =$ 01 12233445 56677889 9AABBCCD

The four most significant bits ($r-1=4$) of MP' are null. The message itself is recovered as the string of the least significant 100 bits ($8z+1-r=100$) of MP' .

1 1223 3445 5667 7889 9AAB BCCD

The signature is accepted because the 510 least significant bits of the recovered message with redundancy MR' are recovered in the extended message with redundancy computed from MP' , exactly as MR from MP .

B.3 Examples with public exponent two

B.3.1 Key production

The public verification exponent v is 2.

Therefore, one secret prime factor is congruent to 3 mod 8 and the other one is congruent to 7 mod 8.

$p =$ 867EA672 E46B2B0A 35F2F2F2 719A1F3C
7EA05947 2B9DAE51 A1730A28 2CDDBBE3
 $q =$ 1 E7468E3C 4869473F 094E7406 60B04CB4
8E47FB50 196544DC C81D4492 8301850F

The public modulus n of 513 bits is of the form $2^{512} + c$,

with $2c > 2^{384} > c$ (form $F_x y_+$ with $x = 8$ and $y = 16$).

$n = p q =$ 1 00000000 00000000 00000000 00000000
97518F6A D742E4E3 A1EDC7F6 CB0F2226
F1343952 4E5466C2 D596A9F9 760FAD26
743E5D43 D9AAA91E F0368F22 B87DF14D

The secret signature exponent s is $(n-p-q+5)/8$.

$s =$ 20000000 00000000 00000000 00000000
12EA31ED 5AE85C9C 743DB8FE D961E444
906DE094 642FFE8F 32CAA860 1478A826
ACEAC115 9294F6BE 10D4C80D 0113D60C

B.3.2 Length of the variables

Because number k is 513,

— number z is valued from 1 to 32, the messages to be signed are strings of 1 to 256 bits, and the padded messages MP and MP' are strings of 1 to 32 bytes;

— number t is 32, the extended messages ME are strings of 32 bytes, and the messages with redundancy MR and MR' are strings of 64 bytes.

Moreover, the intermediate integers IR and IR' and the signatures Σ are strings of 512 bits ($k-1$ bits).

B.3.3 Example 4

This example illustrates the signature of a message of 256 bits with forcing the Jacobi symbol.

F123 E123 D123 C123 B123 A123 9123 8123
7123 6123 5123 4123 3123 2123 1123 0123

Signature process

The message is a string of 256 bits, coded over exactly 32 bytes. Therefore z is 32 and r is 1. The message equals the padded message MP and the extended message ME .

$ME = MP =$ F123E123 D123C123 B123A123 91238123
71236123 51234123 31232123 11230123

The extended message with redundancy MR is a string of 64 bytes.

$MR =$ 12F15823 C3E15823 A3D15823 73C15823
63B15823 B3A15823 D3915823 03815823
F3715823 23615823 43515823 93415823
83315823 53215823 33115823 E3015823

The intermediate integer IR results by truncating MR to 511 bits, by padding to the left one bit valued to 1 and by replacing the least significant byte.

$IR =$ 92F15823 C3E15823 A3D15823 73C15823
63B15823 B3A15823 D3915823 03815823
F3715823 23615823 43515823 93415823
83315823 53215823 33115823 E3015836

Because the Jacobi symbol of IR with respect to n is -1 , the representative element RR is IR'^2 .

$RR = IR'^2 =$ 4978AC11 E1F0AC11 D1E8AC11 B9E0AC11
B1D8AC11 D9D0AC11 E9C8AC11 81C0AC11
F9B8AC11 91B0AC11 A1A8AC11 C9A0AC11
C198AC11 A990AC11 9988AC11 F180AC1B

RR is raised to the power s modulo n . The signature Σ is here the result.

$\Sigma =$ 6BA03660 D7A9001D 533B01A6 05CAFD2A
1352E0D7 8776623C 926FF204 3B93E12B
E7D097AE 50624815 3024E3C1 7CFA565D
F4F76FF2 EC19C507 9D11C723 F0CE5071

Verification process

The signature Σ is less than $n/2$. The resulting integer IS is obtained by squaring Σ mod n .

$IS =$ 0 4978AC11 E1F0AC11 D1E8AC11 B9E0AC11
B1D8AC11 D9D0AC11 E9C8AC11 81C0AC11
F9B8AC11 91B0AC11 A1A8AC11 C9A0AC11
C198AC11 A990AC11 9988AC11 F180AC1B

Because IS is here congruent to 11 mod 16, the recovered intermediate integer IR' is here $2IS$.

$IR' = 2IS =$ 92F15823 C3E15823 A3D15823 73C15823
63B15823 B3A15823 D3915823 03815823
F3715823 23615823 43515823 93415823
83315823 53215823 33115823 E3015836

The recovered message with redundancy MR' is the string of 64 bytes equal to IR' , except for the most significant bit forced to 0 and the least significant byte which is replaced ($(11^{-1}(5)=2)$).

$MR' =$ 12F15823 C3E15823 A3D15823 73C15823
63B15823 B3A15823 D3915823 03815823
F3715823 23615823 43515823 93415823
83315823 53215823 33115823 E3015823

The first non-null sum is the 32-nd sum valued to 1. Thus $z=32$ and $r=1$. The recovered padded message MP' is the string of the 32 bytes of MR' in odd positions.

$MP' =$ F123E123 D123C123 B123A123 91238123
 71236123 51234123 31232123 11230123

The recovered message is a string of 256 bits.

 F123 E123 D123 C123 B123 A123 9123 8123
 7123 6123 5123 4123 3123 2123 1123 0123

The signature is accepted because the 511 least significant bits of the recovered message with redundancy MR' are recovered in the extended message with redundancy computed from MP' , exactly as MR from MP .

B.3.4 Example 5

This last example illustrates the signature of a message of 256 bits without forcing the Jacobi symbol.

 FEDC BA98 7654 3210 FEDC BA98 7654 3210
 FEDC BA98 7654 3210 FEDC BA98 7654 3210

Signature process

The message is a string of 256 bits, coded over exactly 32 bytes. Therefore z is 32 and r is 1. The message equals the padded message MP and the extended message ME .

$ME = MP =$ FEDCBA98 76543210 FEDCBA98 76543210
 FEDCBA98 76543210 FEDCBA98 76543210

The extended message with redundancy MR is a string of 64 bytes.

$MR =$ 1DFEA7DC 6BBAD098 F2764954 85323E10
 1CFEA7DC 6BBAD098 F2764954 85323E10
 1CFEA7DC 6BBAD098 F2764954 85323E10
 1CFEA7DC 6BBAD098 F2764954 85323E10

The intermediate integer IR results by truncating MR to 511 bits, by padding to the left one bit valued to 1 and by replacing the least significant byte. And because the Jacobi symbol of IR with respect to n is +1, IR is here the representative element RR .

$RR = IR =$ 9DFEA7DC 6BBAD098 F2764954 85323E10
 1CFEA7DC 6BBAD098 F2764954 85323E10
 1CFEA7DC 6BBAD098 F2764954 85323E10
 1CFEA7DC 6BBAD098 F2764954 85323E06

RR is raised to the power s modulo n . The result is here the signature Σ .

$\Sigma =$ 28910D1F 0FC8332A 63AFE10A 37848404
 84374DF9 E0A92347 DD1966E5 976823EC
 597A1AEC 0D24FE71 0934D49B 0CB0412F
 E8A10CB0 D39D1C06 207B0000 E9F33021

Verification process

The signature Σ is less than $n/2$. The resulting integer IS is obtained by squaring Σ mod n .

And because IS is here congruent to 6 mod 16, IS is here the recovered intermediate integer IR' .

$IR' = IS =$ 9DFEA7DC 6BBAD098 F2764954 85323E10
 1CFEA7DC 6BBAD098 F2764954 85323E10
 1CFEA7DC 6BBAD098 F2764954 85323E10
 1CFEA7DC 6BBAD098 F2764954 85323E06

The recovered message with redundancy MR' is the string of 64 bytes equal to IR' , except for the most significant bit forced to 0 and the least significant byte which is replaced ($(11^1(3)=1)$).

$MR' =$ 1DFEA7DC 6BBAD098 F2764954 85323E10
 1CFEA7DC 6BBAD098 F2764954 85323E10
 1CFEA7DC 6BBAD098 F2764954 85323E10
 1CFEA7DC 6BBAD098 F2764954 85323E10

The first non-null sum is the 32-nd sum valued to 1. Thus $z=32$ and $r=1$.

The recovered padded message MP' is the string of the 32 bytes of MR' in odd positions.

$MP' =$ FEDCBA98 76543210 FEDCBA98 76543210
 FEDCBA98 76543210 FEDCBA98 76543210

The recovered message is a string of 256 bits.

 FEDC BA98 7654 3210 FEDC BA98 7654 3210
 FEDC BA98 7654 3210 FEDC BA98 7654 3210

The signature is accepted because the 511 least significant bits of the recovered message with redundancy MR' are recovered in the extended message with redundancy computed from MP' , exactly as MR from MP .

Annex C (informative)

Some precautions taken against various potential attacks related to annex A

C.1 Legitimate arguments of the secret function

The only legitimate arguments of the function "raising to the power s modulo n " are the representative elements.

If v is odd, any representative element is a string of $k-1$ bits where the most significant bit is valued to 1 and where the least significant nibble is valued to 6.

If v is even, then one forces to $+1$ the Jacobi symbol of the representative elements with respect to modulus n . And any representative element is a string of

— $k-1$ bits where the most significant bit is valued to 1 and where the least significant nibble is valued to 6 if $(R | n) = +1$.

— $k-2$ bits where the most significant bit is valued to 1 and where the string of the three least significant bits is valued to 3 if $(R | n) = -1$.

C.2 Elimination of four operations

Owing to the structure of the representative elements, the following four operations are eliminated.

NOTE — These informations are the scope of a communication (see annex D) presented at Eurocrypt '90, a workshop held in Århus, Denmark, 1990-05-21/24.

Shift

No string of bits coding a representative element can be shifted into another representative element.

Complementation

No string of bits coding a representative element can be complemented into another representative element.

Natural multiplication

The natural product (i.e. without involving the use of a modulo reduction) of a constant by a representative element is never another representative element.

Natural power

The natural v -th power (i.e. without involving the use of a modulo reduction) of a constant is never a representative element.

As a matter of fact, an integer congruent to 6 modulo 16 is never a power; and an integer congruent to 3 modulo 8 is never an even power.

Annex D
(informative)

Bibliography

- [1] *Precautions taken against various potential attacks in ISO/IEC 9796, Digital signature scheme giving message recovery*, Louis GUILLOU, Jean-Jacques QUISQUATER, Mike WALKER, Peter LANDROCK, Caroline SHAER, Proceedings of Eurocrypt '90, edited by Ivan DAMGÅRD and published by Springer-Verlag in the series "Lecture Notes in Computer Science", Vol 473, pp 465-473.

STANDARDSISO.COM : Click to view the full PDF of ISO/IEC 9796:1991