

ANS X9.82, Part 3 - DRAFT March 2005

**DRAFT X9.82 (Random Number Generation)
Part 3, Deterministic Random Bit Generator
Mechanisms
March 2005**

Contribution of the U.S. Federal Government and not subject to copyright

Contents

1 Scope	9
2 Conformance	9
3 Normative references	10
4 Terms and definitions	10
6 General Discussion and Organization	21
7 DRBG Functional Model.....	23
7.1 Functional Model.....	23
7.2 Functional Model Components.....	23
7.2.1 Introduction.....	23
7.2.2 Entropy Input	24
7.2.3 Other Inputs	24
7.2.4 The Internal State.....	24
7.2.5 The Internal State Transition Function	24
7.2.6 The Output Generation Function	25
7.2.7 Support Functions	25
8. DRBG Concepts and General Requirements	26
8.1 Introduction	26
8.2 DRBG Functions and a DRBG Instantiation.....	26
8.2.1 Functions	26
8.2.2 DRBG Instantiations	26
8.2.3 Internal States	26
8.2.4 Security Strengths Supported by an Instantiation.....	27
8.3 DRBG Boundaries	28
8.4 Seeds	30
8.4.1 General Discussion	30
8.4.2 Generation and Handling of Seeds	30
8.5 Other Inputs to the DRBG	33
8.5.1 Discussion	33
8.5.2 Nonce	33
8.5.3 Personalization String	33

8.5.4 Additional Input	34
8.6 Prediction Resistance and Backtracking Resistance	34
9 DRBG Functions	37
9.1 General Discussion	37
9.2 Instantiating a DRBG	37
9.3 Reseeding a DRBG Instantiation	40
9.4 Generating Pseudorandom Bits Using a DRBG.....	42
9.5 Removing a DRBG Instantiation.....	44
9.6 Auxiliary Functions	45
9.6.1 Introduction.....	45
9.6.2 Derivation Function Using a Hash Function (Hash_df).....	45
9.6.3 Derivation Function Using a Block Cipher Algorithm.....	46
9.6.4 Block_Cipher_Hash Function.....	47
9.7 Self-Testing of the DRBG	48
9.7.1 Discussion	48
9.7.2 Instantiate, Generate, Uninstantiate and Test Functions	50
9.7.3 Generate and Test within a Single DRBG Sub-boundary.....	51
9.7.4 Reseed, Generate and Test within a Single DRBG Sub-boundary	51
9.7.5 Instantiate, Uninstantiate, Generate, Reseed and Test Functions.....	52
9.8 Error Handling	53
10 DRBG Algorithm Specifications	54
10.1 Deterministic RBGs Based on Hash Functions	54
10.1.1 Discussion	54
10.1.2 Hash_DRBG	55
10.1.2.1 Discussion	55
10.1.2.2 Specifications.....	55
10.1.2.2.1 Hash_DRBG Internal State	55
10.1.2.2.2 Instantiation of Hash_DRBG	56
10.1.2.2.3 Reseeding a Hash_DRBG Instantiation.....	57
10.1.2.2.4 Generating Pseudorandom Bits Using Hash_DRBG.....	58
10.1.3 HMAC_DRBG (...)	61
10.1.3.1 Discussion	61

ANS X9.82, Part 3 - DRAFT March 2005

10.1.3.2.2 Specifications	61
10.1.3.2.1.1 HMAC_DRBG Internal State	61
10.1.3.2.2.1 The Update Function (Update).....	62
10.1.3.2.3.1 Instantiation of HMAC_DRBG	63
10.1.3.2.4.1 Reseeding an HMAC_DRBG Instantiation.....	64
10.1.3.2.5.1 Generating Pseudorandom Bits Using HMAC_DRBG	64
10.2 DRBGs Based on Block Ciphers	66
10.2.1 Discussion	66
10.2.2 CTR_DRBG.....	68
10.2.2.1.1 Discussion	68
10.2.2.2.1 Specifications.....	68
10.2.2.2.1.1 CTR_DRBG Internal State	68
10.2.2.2.2.1 The Update Function (Update).....	69
10.2.2.2.3.1 Instantiation of CTR_DRBG	70
10.2.2.2.4.1 Reseeding a CTR_DRBG Instantiation.....	71
10.2.2.2.5.1 Generating Pseudorandom Bits Using CTR_DRBG.....	73
10.2.3 OFB_DRBG	76
10.2.3.1.1 Discussion	76
10.2.3.2.1 Specifications.....	76
10.2.3.2.1.1 OFB_DRBG Internal State	76
10.2.3.2.2.1 The Update Function(Update).....	77
10.2.3.2.3.1 Instantiation of OFB_DRBG (...)	78
10.2.3.2.4.1 Reseeding an OFB_DRBG Instantiation.....	78
10.2.3.2.5.1 Generating Pseudorandom Bits Using OFB_DRBG.....	78
10.3 Deterministic RBGs Based on Number Theoretic Problems.....	79
10.3.1 Discussion	79
10.3.2 Dual Elliptic Curve Deterministic RBG (Dual_EC_DRBG).....	79
10.3.2.1.1 Discussion	79
10.3.2.2.1 Specifications.....	82
10.3.2.2.1.1 Dual_EC_DRBG Internal State and Other Specification Details.....	82
10.3.2.2.2.1 Instantiation of Dual_EC_DRBG	82
10.3.2.2.3.1 Reseeding of a Dual_EC_DRBG Instantiation	84

ANS X9.82, Part 3 - DRAFT March 2005

10.3.2.2.4 Generating Pseudorandom Bits Using Dual_EC_DRBG	85
10.3.3 Micali-Schnorr Deterministic RBG (MS_DRBG).....	88
10.3.3.1 Discussion	88
10.3.3.2 MS_DRBG Specifications.....	90
10.3.3.2.1 Internal State for MS_DRBG	90
10.3.3.2.2 Selection of the M-S parameters	90
10.3.3.2.3 Instantiation of MS_DRBG	91
10.3.3.2.4 Reseeding of a MS_DRBG Instantiation.....	93
10.3.3.2.5 Generating Psuedorandom Bits Using MS_DRBG	94
11 Assurance	97
11.1 Overview.....	97
11.2 Minimal Documentation Requirements	98
11.3 Implementation Validation Testing.....	98
11.4 Operational/Health Testing	98
11.4.1 Overview	98
11.4.2 Known Answer Testing	99
Annex A: (Normative) Application-Specific Constants	100
A.1 Constants for the Dual_EC_DRBG	100
A.1.1 Curves over Prime Fields	100
A.1.1.1 Curve P-224	100
A.1.1.2 Curve P-256	101
A.1.1.3 Curve P-384	101
A.1.1.4 Curve P-521	102
A.1.2 Curves over Binary Fields	102
A.1.2.1 Curve K-233	103
A.1.2.3 Curve B-233	104
A.1.2.2 Curve K-283	105
A.1.2.4 Curve B-283	105
A.1.2.5 Curve K-409	106
A.1.2.6 Curve B-409	107
A.1.2.7 Curve K-571	108

ANS X9.82, Part 3 - DRAFT March 2005

A.1.2.8 Curve B-571	109
A.2 Test Moduli for the MS_DRBG (...)	110
A.2.1 The Test Modulus <i>n</i> of Size 2048 Bits	111
A.2.2 The Test Modulus <i>n</i> of Size 3072 Bits	111
ANNEX B : (Normative) Conversion and Auxilliary Routines	112
B.1 Bitstring to an Integer	112
B.2 Integer to a Bitstring	112
B.3 Integer to an Octet String.....	112
B.4 Octet String to an Integer.....	113
Annex C: (Informative) Security Considerations	114
C.1 The Security of Hash Functions	114
C.2 Algorithm and Keysize Selection.....	114
C.3 Extracting Bits in the Dual_EC_DRBG (...)	116
C.3.1 Potential Bias Due to Modular Arithmetic for Curves Over F_p	116
C.3.2 Adjusting for the missing bit(s) of entropy in the x coordinates.....	116
ANNEX D: (Informative) Functional Requirements	120
D.1 General Functional Requirements.....	120
D.2 Functional Requirements for Entropy Input.....	120
D.3 Functional Requirements for Other Inputs.....	120
D.4 Functional Requirements for the Internal State	121
D.5 Functional Requirements for the Internal State Transition Function.....	121
D.6 Functional Requirements for the Output Generation Function.....	122
D.7 Functional Requirements for Support Functions	123
ANNEX E: (Informative) DRBG Selection	125
E.1 Choosing a DRBG Algorithm	125
E.2 DRBGs Based on Hash Functions.....	125
E.2.1 Hash_DRBG	126
E.2.1.1 Implementation Issues.....	126
E.2.1.2 Performance Properties	126
E.2.2 HMAC_DRBG	126
E.2.2.1 Implementation Properties	127

ANS X9.82, Part 3 - DRAFT March 2005

E.2.2.2 Performance Properties.....	127
E.2.3 Summary and Comparison of Hash-Based DRBGs.....	128
E.2.3.1 Security	128
E.2.3.2 Performance / Implementation Tradeoffs	129
E.3 DRBGs Based on Block Ciphers	130
E.3.1 The Two Constructions: CTR and OFB.....	130
E.3.2 Choosing a Block Cipher.....	130
E.3.3 Conditioned Entropy Sources and the Derivation Function.....	132
E.4 DRBGs Based on Hard Problems.....	132
E.4.1 Implementation Considerations	133
E.4.1.1 Dual_EC_DRBG	133
E4.1.2. Micali-Schnorr.....	133
ANNEX F: (Informative) Example Pseudocode for Each DRBG.....	135
F.1 Preliminaries.....	135
F.2 Hash_DRBG Example	135
F.2.1 Discussion	135
F.2.2 Instantiation of Hash_DRBG	136
F.2.3 Reseeding a Hash_DRBG Instantiation	137
F.2.4 Generating Pseudorandom Bits Using Hash_DRBG.....	138
F.3 HMAC_DRBG Example.....	141
F.3.1 Discussion	141
F.3.2 Instantiation of HMAC_DRBG	141
F.3.3 Generating Pseudorandom Bits Using HMAC_DRBG.....	143
F.4 CTR_DRBG Example	144
F.4.1 Discussion	144
F.4.2 The Update Function	145
F.4.3 Instantiation of CTR_DRBG.....	145
F.4.4 Reseeding a CTR_DRBG Instantiation.....	147
F.4.5 Generating Pseudorandom Bits Using CTR_DRBG	148
F.5 OFB_DRBG Example.....	151
F.5.1 Discussion	151
F.5.2 The Update Function	151

ANS X9.82, Part 3 - DRAFT March 2005

F.5.3 Instantiation of OFB_DRBG.....	152
F.5.4 Reseeding the OFB_DRBG Instantiation	153
F.5.5 Generating Pseudorandom Bits using OFB_DRBG	154
F.6 Dual_EC_DRBG Example.....	156
F.6.1 Discussion	156
F.6.2 Instantiation of Dual_EC_DRBG.....	157
F.6.3 Reseeding a Dual_EC_DRBG Instantiation	160
F.6.4 Generating Pseudorandom Bits Using Dual_EC_DRBG	161
F.7 MS_DRBG Example.....	162
F.7.1 Discussion	162
F.7.2 Instantiation of MS_DRBG.....	163
F.7.3 Reseeding an MSDRBG Instantiation	166
F.7.4 Generating Pseudorandom Bits Using MS_DRBG.....	167
ANNEX G: (Informative) Bibliography	170

Random Number Generation

Part 3: Deterministic Random Bit Generator Mechanisms

Contribution of the U.S. Federal Government and not subject to copyright

1 Scope

This part of ANSI X9.82 defines techniques for the generation of random bits using deterministic methods. This part includes:

1. A model for a deterministic random bit generator,
2. Requirements for deterministic random bit generator mechanisms,
3. Specifications for deterministic random bit generator mechanisms that use hash functions, block ciphers and number theoretic problems,
4. Implementation issues, and
5. Assurance considerations.

The precise structure, design and development of a random bit generator is outside the scope of this standard.

This part of ANS X9.82 specifies several diverse DRBG mechanisms, all of which provided acceptable security when this Standard was approved. However, in the event that new attacks are found on a particular class of mechanisms, a diversity of approved mechanisms will allow a timely transition to a different class of DRBG mechanism.

Random number generation does not require interoperability between two entities, e.g., communicating entities may use different DRBG mechanisms without affecting their ability to communicate. Therefore, an entity may choose a single appropriate DRBG mechanism for their applications: see Annex E for a discussion of DRBG selection.

2 Conformance

An implementation of a deterministic random bit generator (DRBG) may claim conformance with ANSI X9.82 if it implements the mandatory provisions of Part 1, the mandatory requirements of one or more of the DRBG mechanisms specified in this part of the Standard, an entropy source from Part 2 and the appropriate mandatory requirements of Part 4.

Conformance can be assured by a testing laboratory associated with the Cryptographic Module Validation Program (CMVP) (see <http://csrc.nist.gov/cryptval>). Although an implementation may claim conformance with the Standard apart from such testing, implementation testing through the CMVP is strongly recommended.

3 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. Nevertheless, parties to agreements based on this document are encouraged to consider applying the most recent edition of the referenced documents indicated below. For undated references, the latest edition of the referenced document (including any amendments) applies.

ANS X9.52-1998, *Triple Data Encryption Algorithm Modes of Operation*.

ANS X9.62-2000, *Public Key Cryptography for the Financial Services Industry - The Elliptic Curve Digital Signature Algorithm (ECDSA)*.

ANS X9.63-2000, *Public Key Cryptography for the Financial Services Industry - Key Agreement and Key Transport Using Elliptic Key Cryptography*.

ANS X9.82, Part 1-200x, *Overview and Basic Principles*, Draft.

ANS X9.82, Part 2-200x, *Entropy Sources*, Draft.

ANS X9.82, Part 4-200x, *RBG Constructions*, Draft.

FIPS 180-2, *Secure Hash Standard (SHS)*, August 2002; ASC X9 Registry 00003.

FIPS 197, *Advanced Encryption Standard (AES)*, November 2001; ASC X9 Registry 00002.

FIPS 198, *Keyed-Hash Message Authentication Code (HMAC)*, March 6, 2002; ASC X9 Registry 00004.

4 Terms and definitions

For the purposes of this part of the Standard, the following terms and definitions apply.

4.

Algorithm

A clearly specified mathematical process for computation; a set of rules that, if followed, will give a prescribed result.

4.

Approved

An X9 approved resource is one that is either specified as (or within) a current X9 standard, or listed in the X9 Registry.

4.

Backtracking Resistance

The assurance that the output sequence from an RBG remains indistinguishable from an

ANS X9.82, Part 3 - DRAFT – March 2005

ideal random sequence even to an attacker who compromises the RBG in the future, up to the claimed security strength of the RBG. For example, an RBG that allowed an attacker to "backtrack" from the current working state to generate prior outputs would not provide backtracking resistance. The complementary assurance is called Prediction Resistance.

4.

Biased

A bitstring (or number) that is chosen from a sample space is said to be biased if one bitstring (or number) is more likely to be chosen than another bitstring (or number). Contrast with unbiased.

4.

Bitstring

A bitstring is an ordered sequence of 0's and 1's. The leftmost bit is the most significant bit of the string and is the newest bit generated. The rightmost bit is the least significant bit of the string.

4.

Bitwise Exclusive-or

An operation on two bitstrings of equal length that combines corresponding bits of each bitstring using an exclusive-or operation.

4.

Block Cipher

A symmetric key cryptographic algorithm that transforms a block of information at a time using a cryptographic key. For a block cipher algorithm, the length of the input block is the same as the length of the output block.

4.

Consuming Application

The application that uses random numbers or bits obtained from an Approved random bit generator

4.

Cryptographic Key (Key)

A parameter that determines the operation of a cryptographic function such as:

1. The transformation from plain text to cipher text and vice versa,

ANS X9.82, Part 3 - DRAFT – March 2005

2. The synchronized generation of keying material,
3. A digital signature computation or validation.

4.

Deterministic Algorithm

An algorithm that, given the same inputs, always produces the same outputs.

4.

Deterministic Random Bit Generator (DRBG)

An RBG that uses a deterministic algorithm to produce a pseudorandom sequence of bits from a secret initial value called a *seed* (which contains entropy and possibly a personalization string) along with other possible inputs. Additional non-deterministic inputs may allow periodic reseeding. The outputs do not always contain full entropy, contrast this with an NRBG. A DRBG is often called a Pseudorandom Number (or Bit) Generator. A DRBG has an assessed security strength and is designed with the goal of requiring an adversary to do at least the amount of work associated with that security strength in order to distinguish the output from an ideal random sequence.

4.

DRBG Boundary

A conceptual boundary that is used to explain the operations of a DRBG and its interaction with and relation to other processes.

4.

Entropy

A measure of the disorder, randomness or variability in a closed system. The entropy of X is a mathematical measure of the amount of information provided by an observation of X . As such, entropy is always relative to an observer and his or her knowledge prior to an observation. Also, see min-entropy.

4.

Entropy Input

The input to an RBG of a string of bits that contains entropy, that is, the entropy input is digitized and is assessed. For an NRBG, this is obtained from an entropy source. For a DRBG, this is included in the seed material.

4.

Entropy Input Source

A source of unpredictable data, such as thermal noise or hard drive seek times. There is no assumption that the unpredictable data has a uniform distribution.

4.

Equivalent Process

Two processes are equivalent if, when the same values are input to each process, the same output is produced.

4.

Exclusive-or

A mathematical operation, symbol \oplus , defined as:

$$0 \oplus 0 = 0$$

$$0 \oplus 1 = 1$$

$$1 \oplus 0 = 1 \text{ and}$$

$$1 \oplus 1 = 0.$$

Equivalent to binary addition without carry.

4.

Full entropy

An m -bit string has full entropy if every m -bit value is equally likely to occur.

4.

Hash Function

A (mathematical) function that maps values from a large (possibly very large) domain into a smaller range. The function satisfies the following properties:

1. (One-way) It is computationally infeasible to find any input that maps to any pre-specified output;
2. (Collision free) It is computationally infeasible to find any two distinct inputs that map to the same output.

4.

Implementation

An implementation of an RBG is a cryptographic device or portion of a cryptographic device that is the physical embodiment of the RBG design, for example, some code running on a computing platform. An implementation may be designed to handle more than one instantiation at a time.

4.

Implementation Testing for Validation

Testing by an independent and accredited party to ensure that an implementation of a standard conforms to the specifications of that standard.

4.

Instantiation of an RBG

An instantiation of an RBG is a specific, logically independent, initialized RBG. One instantiation is distinguished from another by a handle (e.g., an identifying number).

4.

Internal State

The collection of stored information about an RBG instantiation. This can include both secret and non-secret information.

4.

Internal State Transition Functions

The set of functions that cause a particular internal state in an instantiation to be updated so that a new internal state is the result.

4.

Key

See Cryptographic Key.

4.

Non-Deterministic Random Bit Generator (Non-deterministic RBG) (NRBG)

An RBG that produces output that is fully dependent on some unpredictable physical source that produces entropy. Contrast with a DRBG. Other names for non-deterministic RBGs are True Random Number (or Bit) Generators and, simply, Random Number (or Bit) Generators.

4.

Operational Testing

Testing within an implementation immediately prior to or during normal operation to determine that the implementation continues to perform as implemented and optionally validated.

4.

Output Generation Function

The function in an RBG that outputs bits that appear to be random, that is, conform with the ideal random distribution.

4.

Personalization String

An optional string of bits that is combined with a secret input and a nonce to produce a seed.

4.

Prediction Resistance

A compromise of the DRBG internal state has no effect on the security of future DRBG outputs. If a compromise of *State_x* occurs, *prediction resistance* provides assurance that the output sequence resulting from states *after* the compromise remains secure. That is, an adversary who is given access to all of any subset of the output sequence after the compromise cannot distinguish it from random; if the adversary knows only part of the future output sequence, an adversary he cannot predict any bit of that future output sequence that he has not already seen. The complementary assurance is called Backtracking Resistance.

4.

Pseudorandom

A process or data produced by a process is said to be pseudorandom when the outcome is deterministic, yet also effectively random as long as the internal action of the process is hidden from observation. For cryptographic purposes, “effectively” means “within the limits of the intended cryptographic strength.” Note: Non-cryptographic use of “pseudorandom” has less stringent meanings for “effectively.”

4.

Pseudorandom Number Generator

See Deterministic Random Bit Generator.

ANS X9.82, Part 3 - DRAFT – March 2005

4.

Public Key

In an asymmetric (public) key cryptosystem, that key of an entity's key pair that is publicly known.

4.

Public Key Pair

In an asymmetric (public) key cryptosystem, the public key and associated private key.

4.

Random Number

For the purposes of this standard, a value in a set that has an equal probability of being selected from the total population of possibilities and hence is unpredictable. A random number is an instance of an unbiased random variable, that is, the output produced by a uniformly distributed random process.

4.

Random Bit Generator (RBG)

A device or algorithm that outputs a sequence of binary bits that appears to be statistically independent and unbiased.

4.

Random Number Generator (RNG)

A device or algorithm that can produce a sequence of random numbers that appears to be from an ideal random distribution.

4.

Reseed

To acquire additional bits with sufficient entropy for the desired security strength.

4.

Security Strength

A number associated with the amount of work (that is, the number of operations) that is required to break a cryptographic algorithm or system; a security strength is specified in bits and is a specific value from the set (112, 128, 192, 256). The amount of work needed is 2 raised to the security strength.

ANS X9.82, Part 3 - DRAFT – March 2005

4.

Seed

Noun : A string of bits that is used as input to a Deterministic Random Bit Generator (DRBG). The seed will determine a portion of the internal state of the DRBG, and its entropy must be sufficient to support the security strength of the DRBG. [New]

Verb : To acquire bits with sufficient entropy for the desired security strength. These bits will be used as input to a DRBG to determine a portion of the initial internal state. Contrast with reseed.

4.

Seed Period

The period of time between initializing a DRBG with one seed and reseeding that DRBG with another seed.

4.

Sequence

An ordered set of quantities.

4.

Shall

Used to indicate a requirement of this Standard.

4.

Should

Used to indicate a highly desirable feature for a DRBG that is not necessarily required by this Standard.

4.

Statistically Unique

A value is said to be statistically unique when it has a negligible probability to occur again in a set of such values. When a random value is required to be statistically unique, it may be selected either with or without replacement from the sample space of possibilities; this is in contrast to when a value is required to be unique, as then it must be selected without replacement.

4.

String

See Sequence.

4.

Supporting Functions

The set of functions in an RBG that are needed for assurance of correct operation but that do not change the internal state. An example of a Supporting Function is the known answer tests that are run at startup on a DRBG.

Comment [ebb1]: Page: 18
Can this be removed ?

4.

Unbiased

A bitstring (or number) that is chosen from a sample space is said to be unbiased if all potential bitstrings (or numbers) have the same probability of being chosen. Contrast with biased.

4.

Unpredictable

In the context of random bit generation, an output bit is unpredictable if an adversary has only a negligible advantage (that is, essentially not much better than chance) in predicting it correctly.

4.

Working State

A subset of the internal state that is used by a DRBG to produce pseudorandom bits at a given point in time. The working state (and thus, the internal state) is updated to the next state prior to producing another string of pseudorandom bits.

5 Symbols and abbreviated terms

The following abbreviations are used in this document:

Abbreviation	Meaning
AES	Advanced Encryption Standard.
ANS	American National Standard
ANSI	American National Standards Institute.
ASC	Accredited Standards Committee
DRBG	Deterministic Random Bit Generator.
ECDLP	Elliptic Curve Discrete Logarithm Problem.
FIPS	Federal Information Processing Standard.
HMAC	Keyed-Hash Message Authentication Code.
NRBG	Non-deterministic Random Bit Generator.
RBG	Random Bit Generator.
TDEA	Triple Data Encryption Algorithm.

The following symbols are used in this document.

Symbol	Meaning
$+$	Addition
$\lceil X \rceil$	Ceiling: the smallest integer $\geq X$. For example, $\lceil 5 \rceil = 5$, and $\lceil 5.3 \rceil = 6$.
$X \oplus Y$	Bitwise exclusive-or (also bitwise addition mod 2) of two bitstrings X and Y of the same length.
$X \parallel Y$	Concatenation of two strings X and Y . X and Y are either both bitstrings, or both octet strings.
$\gcd(x, y)$	The greatest common divisor of the integers x and y .
$\text{len}(a)$	The length in bits of string a .
$x \bmod n$	The unique remainder r (where $0 \leq r \leq n-1$) when integer x is divided by n . For example, $23 \bmod 7 = 2$.

ANS X9.82, Part 3 - DRAFT – March 2005

	Used in a figure to illustrate a "switch" between sources of input.
$\{a_1, \dots a_l\}$	The internal state of the DRBG at a point in time. The types and number of the a_i depends on the specific DRBG.
0^x	A string of x zero bits.

6 General Discussion and Organization

Part 1 of this Standard (*Random Number Generation, Part 1: Overview and Basic Principles*) describes several cryptographic applications for random numbers, specifies the characteristics for random numbers and random number generators, and provides mathematical and cryptographic background information on the concept of randomness. Random bit generators are used for the generation of random numbers. Part 1 specifies requirements for random bit generators that are applicable to both non-deterministic random bit generators (NRBGs) and deterministic random bit generators (DRBGs). In addition, Part 1 also introduces a general functional model and a conceptual cryptographic Application Programming Interface (API) for random bit generators.

Part 2 of this Standard (*Entropy Sources*) discusses entropy sources used by random bit generators. In the case of DRBGs, the entropy sources are required to seed and reseed the DRBG.

Part 4 of this Standard (*Random Bit Generator Constructions*) provides guidance on combining components to construct random bit generators.

This part of the Standard (*Random Number Generation, Part 3: Deterministic Random Bit Generator Mechanisms*) specifies Approved DRBG mechanisms. A DRBG mechanism is an RBG component that utilizes an algorithm to produce a sequence of bits from an initial internal state that is determined by an input that is commonly known as a seed. Because of the deterministic nature of the process, a DRBG mechanism is said to produce “pseudorandom” rather than random bits, i.e., the string of bits produced by a DRBG mechanism is predictable and can be reconstructed, given knowledge of the algorithm, the seed and any other input information. However, if the input is kept secret, and the algorithm is well designed, the bitstrings will appear to be random. A process or data produced by a process is said to be pseudorandom when the outcome is deterministic.

The seed for a DRBG mechanism requires that sufficient entropy be provided during instantiation and reseeding (see Parts 2 and 4 of this Standard). While a DRBG mechanism may conform to this part of the Standard (i.e., Part 3), an implementation cannot achieve the goals specified in Part 1 unless the entropy input source is included as specified in Part 4. That is, the security of an RBG that uses a DRBG mechanism is a system implementation issue; both the DRBG mechanism and its entropy input source must be considered.

Throughout the remainder of this document, the term “DRBG mechanism” has been shortened to “DRBG”.

The remaining sections of this part of the Standard are organized as follows:

- Section 7 provides a functional model for a DRBG that particularizes the functional model of Part 1.
- Section 8 provides DRBG concepts and general requirements.

Comment [ebb2]: Page: 21
Mike to provide alternate text ?

ANS X9.82, Part 3 - DRAFT – March 2005

- Section 9 specifies the DRBG functions that will be used to access the DRBG algorithms specified in Section 10.
- Section 10 specifies Approved DRBG algorithms.
- Section 11 addresses assurance issues for DRBGs.

This part of the Standard also includes the following normative annexes:

- Annex A specifies additional DRBG-specific information.
- Annex B provides conversion routines.
- Annex C discusses security considerations for selecting and implementing DRBGs.

The following informative annexes are also included:

- Annex D discusses the functional requirements specified in Part 1 as they are fulfilled by this part of the Standard.
- Annex E provides a discussion on DRBG selection.
- Annex F provides example pseudocode for each DRBG.
- Annex G provides a bibliography for related informational material.

7 DRBG Functional Model

7.1 Functional Model

Part 1 of this Standard provides a general functional model for random bit generators (RBGs). Figure 1 particularizes the functional model of Part 1 for DRBGs.

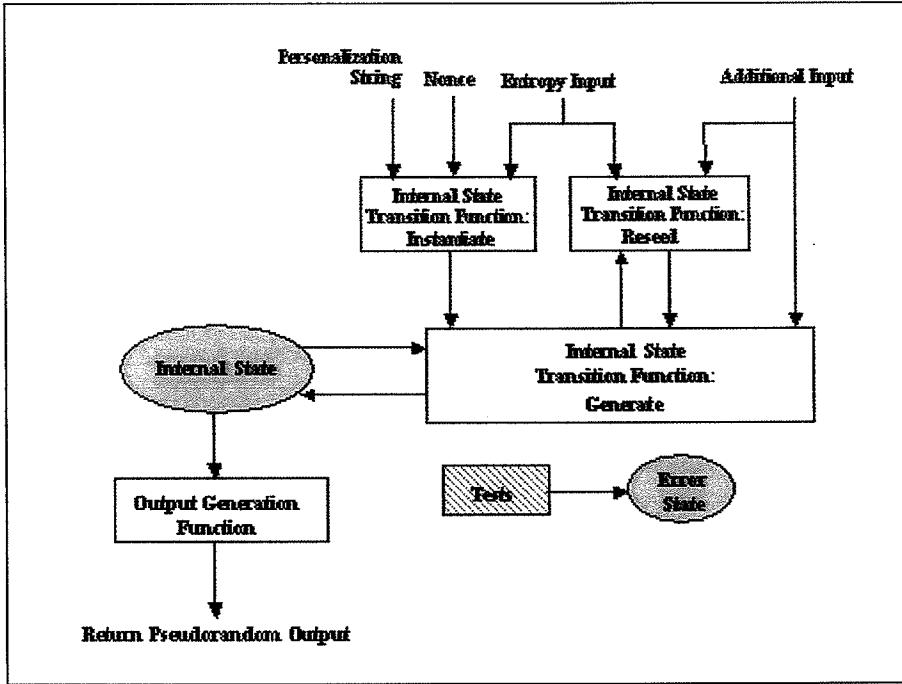


Figure 1: DRBG Model

7.2 Functional Model Components

7.2.1 Introduction

Part 1 of this Standard provides general functional requirements for random bit generators. These requirements are discussed briefly in this section. Annex D provides a discussion of how each functional requirement in Part 1 is fulfilled by the requirements for DRBGs in this part of the Standard.

7.2.2 Entropy Input

The entropy input, as discussed in Part 1, is provided to a DRBG for the seed (see Section 8.4.2). The entropy input and the seed **shall** be kept secret. The secrecy of this information provides the basis for the security of the DRBG. At a minimum, the entropy input **shall** provide the requested amount of entropy for a DRBG. Appropriate sources for the entropy input are discussed in Parts 2 and 4 of this Standard.

The DRBGs, as specified in this part of the Standard and further discussed in Part 4, allow for some bias in the entropy input. Whenever a bitstring containing entropy is required by the DRBG, a request is made that indicates the minimum amount of entropy to be returned; the request may obtain entropy input bits from a buffer containing readily available entropy bits or may cause entropy input bits to be created. The request may be fulfilled by a bitstring that is equal to or greater in length to the requested entropy. The DRBG expects that the returned bitstring will contain at least the amount of entropy requested. Additional entropy beyond the amount requested is not required, but is desirable.

7.2.3 Other Inputs

Other information may be obtained by a DRBG as input. This information may or may not be required to be kept secret by a consuming application; however, the security of the DRBG itself does not rely on the secrecy of this information. The information **should** be checked for validity when possible.

During DRBG instantiation, a nonce is required and is combined with the entropy input to create the initial DRBG seed. Criteria for the nonce are provided in Section 8.5.2.

This Standard recommends the insertion of a personalization string during DRBG instantiation; when used, the personalization string is combined with the entropy bits and a nonce to create the initial DRBG seed. The personalization string **shall** be unique for all instantiations of the same DRBG type (e.g., Hash_DRBG). See Section 8.5.3 for additional discussion on personalization strings.

Additional input may also be provided during reseeding and when pseudorandom bits are requested. See Section 8.5.4 for a discussion of this input.

7.2.4 The Internal State

The internal state is the memory of the DRBG and consists of all of the parameters, variables and other stored values that the DRBG uses or acts upon. The internal state contains both administrative data and data that is acted upon and/or modified during the generation of pseudorandom bits (i.e., the *working state*). The contents of the internal state is dependent on the specific DRBG and includes all information that is required to produce the pseudorandom bits from one request to the next.

7.2.5 The Internal State Transition Function

An internal state transition function handles the DRBG's internal state. The DRBGs in this

Standard have four separate state transition functions:

1. During the initial instantiation of the DRBG, a seed is created and is used to determine the initial internal state.
2. Each request for pseudorandom bits produces the requested bits using the current internal state and determines a new internal state that is used for the next request of bits.
3. When an application determines that reseeding of the DRBG is required, a reseed function creates a new seed and determines a new internal state for the next request for pseudorandom bits.
4. When a consuming application or a testing process no longer requires an instantiation, the internal state is released.

7.2.6 The Output Generation Function

The output generation function of a DRBG produces pseudorandom bits that are a function of the internal state of the DRBG and any input that is introduced while the internal state transition function is operating. These pseudorandom output bits are deterministic with respect to the input information. Any formatting of the output bits prior to output is determined by a particular implementation.

7.2.7 Support Functions

The support functions for a DRBG are concerned with assessing and reacting to the health of the DRBG. The health tests are discussed in Sections 9.7 and 11.4.

8. DRBG Concepts and General Requirements

8.1 Introduction

This section provides concepts and general requirements for the implementation and use of a DRBG. The DRBG functions are explained and requirements for an implementation are provided.

8.2 DRBG Functions and a DRBG Instantiation

8.2.1 Functions

A DRBG requires instantiate, uninstantiate, generate, and testing functions. A DRBG **may** also include a reseed function. A DRBG **shall** be instantiated prior to the generation of output by the DRBG. The instantiate function initializes the internal state using a seed; the uninstantiate function zeroizes (i.e., erases) the internal state. The generate function generates pseudorandom bits upon request. The reseed function modifies the internal state using a new seed. The testing function is intended to test the continued “health” of the DRBG.

8.2.2 DRBG Instantiations

A DRBG **may** be used to obtain pseudorandom bits for different purposes (e.g., DSA private keys and AES keys) and **should** be separately instantiated for each purpose. However, it may not always be practical for an application to use multiple instantiations. For example, if an application cannot support multiple instantiations (e.g., because of memory restrictions), then the same instantiation could be associated with generating both RSA keys and AES keys.

A DRBG is instantiated using a seed and **may** be reseeded; when reseeded, the seed **shall** be different than the seed used for instantiation. Each seed defines a *seed period* for the DRBG instantiation; an instantiation consists of one or more seed periods that begin when a new seed is acquired (see Figure 2).

8.2.3 Internal States

During instantiation, an

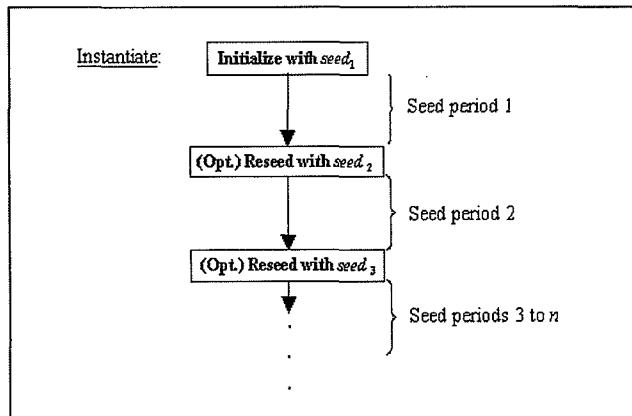


Figure 2: DRBG Instantiation

initial internal state is derived from the seed. The internal state for an instantiation includes:

1. Working state:
 - a. One or more values that are derived from the seed and become part of the internal state; these values must usually remain secret, and
 - b. A count of the number of requests since the last seed or reseed.
2. Administrative information (e.g., security strength provided by the DRBG).

The internal state **shall** be protected at least as well as the intended use of the pseudorandom output bits requested by the consuming application. Each DRBG instantiation **shall** have its own internal state. The internal state for one DRBG instantiation **shall not** be used as the internal state for a different instantiation.

A DRBG transitions between internal states when the generator is requested to provide new pseudorandom bits. A DRBG **may** also be implemented to transition in response to internal or external events (e.g., system interrupts) or to transition continuously (e.g., whenever time is available to run the generator).

A DRBG implementation **may** be designed to handle multiple instantiations. Sufficient space must be available for the expected number of instantiations, i.e., sufficient memory must be available to store the internal state associated with each instantiation.

8.2.4 Security Strengths Supported by an Instantiation

The DRBGs specified in this Standard support four security strengths: 112, 128, 192 or 256 bits. The actual security strength supported by a given instantiation depends on the DRBG implementation and on the amount of entropy provided to the instantiate function. Note that the security strength actually supported by a particular instantiation **may** be less than the maximum security strength possible for that DRBG implementation (see Table 1). For example, a DRBG that is designed to support a maximum security strength of 256 bits may be instantiated to support only a 128-bit security strength.

Table 1: Possible Instantiated Security Strengths

Maximum Designed Security Strength	112	128	192	256
Possible Instantiated Security Strengths	112	112, 128	112, 128, 192	112, 128, 192, 256

A security strength for the instantiation is requested by a consuming application during instantiation, and the instantiate function obtains the appropriate amount of entropy for the requested security strength. Any security strength may be requested, but the DRBG will only be instantiated to one of the four security strengths above, depending on the DRBG implementation. A requested security strength that is below the 112-bit security strength or

is between two of the four security strengths will be instantiated to the next highest level (e.g., a requested security strength of 96 bits will result in an instantiation at the 112-bit security strength).

Following instantiation, requests can be made to the generate function for pseudorandom bits. For each generate request, a security strength to be provided for the bits is requested. Any security strength can be requested up to the security strength of the instantiation, e.g., an instantiation could be instantiated at the 128-bit security strength, but a request for pseudorandom bits could indicate that a lesser security strength is actually required for the bits to be generated. The generate function checks that the requested security strength does not exceed the security strength for the instantiation. Assuming that the request is valid, the requested number of bits is returned.

When an instantiation is used for multiple purposes, the minimum entropy requirement for each purpose must be considered. The DRBG needs to be instantiated for the highest security strength required. For example, if one purpose requires a security strength of 112 bits, and another purpose requires a security strength of 256 bits, then the DRBG **shall** be instantiated to support the 256-bit security strength.

8.3 DRBG Boundaries

As a convenience, this Standard uses the notion of a “DRBG boundary” to explain the operations of a DRBG and its interaction with and relation to other processes; a DRBG boundary contains all DRBG functions and internal states required for a DRBG. A DRBG boundary is entered via the DRBG’s public interfaces, which are made available to consuming applications.

Within a DRBG boundary,

1. The DRBG internal state and the operation of the DRBG functions **shall** only be affected according to the DRBG specification.
2. The DRBG internal state **shall** exist solely within the DRBG boundary. The internal state **shall** be contained within the DRBG boundary and **shall not** be accessed by non-DRBG functions.
3. Information about secret parts of the DRBG internal state and intermediate values in computations involving these secret parts **shall not** affect any information that leaves the DRBG boundary, except as specified for the DRBG pseudorandom bit outputs.

Each DRBG includes one or more cryptographic primitives (e.g., a hash function). Other applications may use the same cryptographic primitive as long as the DRBG’s internal state and the DRBG functions are not affected.

A DRBG’s functions may be contained within a single device, or may be distributed across multiple devices (see Figures 3 and 4). Figure 3 depicts a DRBG for which all functions are contained within the same device. In this case, there is a single DRBG boundary.

Figure 4 provides an example of DRBG functions that are distributed across multiple devices. In this case, each device has a DRBG sub-boundary that contains the DRBG functions implemented on that device, and the boundary around the entire DRBG consists of the aggregation of sub-boundaries providing the DRBG functionality. The use of distributed DRBG functions may be convenient for restricted environments (e.g., smart card applications) in which the primary use of the DRBG does not require repeated use of the instantiate or reseed functions.

Each DRBG boundary or sub-boundary **shall** contain a test function to test the “health” of other DRBG functions within that boundary. Although the seed is shown in the figures as originating outside the DRBG boundary, it may originate from within the boundary. Part 4 discusses the construction of an RBG that includes both the DRBG and the entropy input for the seed.

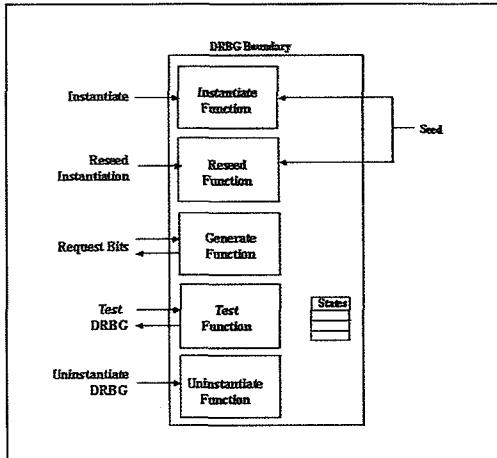


Figure 3: DRBG Functions within a Single Device

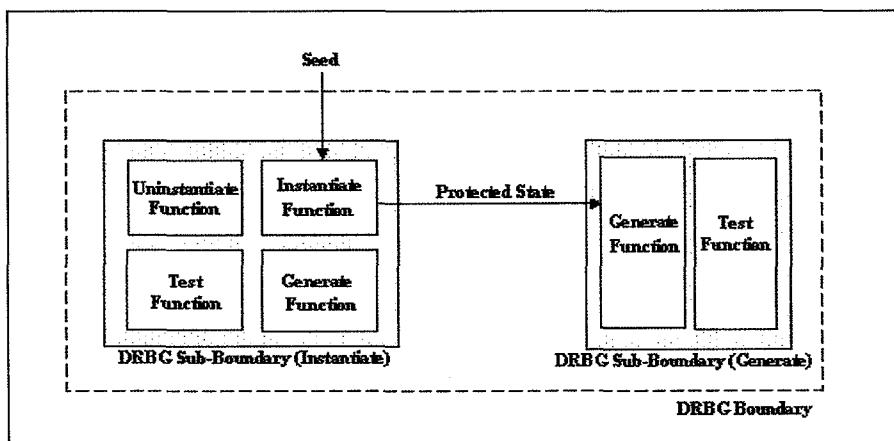


Figure 4: Distributed DRBG Functions

Distributed DRBG boundaries **shall** be subject to the following:

1. Any DRBG boundary or sub-boundary that includes an instantiate function **shall** include uninstantiate, generate and test functions to facilitate health testing. Note that in this case, the generate function may not be the “primary” generate function for the DRBG. For example, for a smart card application, it may be necessary to distribute the DRBG functions so that the smart card contains only the generate function, along with its associated testing function. In this case, the instantiate function may reside on the system that initializes the smart card; the generate and uninstantiate functions are used on this system during the testing of the instantiate function.
2. A DRBG boundary or sub-boundary containing a generate function **shall** include a test function.
3. A DRBG boundary or sub-boundary that contains a reseed function **shall** include generate and test functions to facilitate health testing. Note that as in case 1, the generate function may not be the “primary” generate function for the DRBG.

When DRBG functions are distributed, appropriate mechanisms **shall** be used to protect the confidentiality and integrity of the internal state or parts of the internal state that are transferred between the distributed DRBG sub-boundaries. The confidentiality and integrity mechanisms and security strength **shall** be consistent with the data to be protected by the DRBG’s consuming application (see SP 800-57).

8.4 Seeds

8.4.1 General Discussion

When a DRBG is used to generate pseudorandom bits, a seed **shall** be acquired prior to the generation of output bits by the DRBG. The seed is used to instantiate the DRBG and determine the initial internal state that is used when calling the DRBG to obtain the first output bits.

Reseeding is a means of recovering the secrecy of the output of the DRBG if a seed or the internal state becomes known. Periodic reseeding is a good countermeasure to the potential threat that the seeds and DRBG output become compromised. In some implementations (e.g., smartcards), an adequate reseeding process may not be possible. In these cases, the best policy might be to replace the DRBG, obtaining a new seed in the process (e.g., obtain a new smart card).

8.4.2 Generation and Handling of Seeds

The seed and its use by a DRBG **shall** be generated and handled as follows:

1. Seed construction for instantiation: The seed material used to determine a seed for instantiation consists of one to three components: entropy input, a nonce and a personalization string. Entropy input **shall** always be used in the construction of a seed; requirements for the entropy input are discussed in item 3. Except as noted

below, a nonce **shall** also be used; requirements for the nonce are discussed in Section 8.5.2. This Standard also recommends the inclusion of a personalization string; requirements for the personalization string are discussed in Section 8.5.3. Depending on the DRBG and the source of the entropy input, a derivation function is required to derive a seed from the seed material. Figure 5 depicts the general seed construction process for instantiation.

When full entropy input is readily available, the DRBGs based on block cipher algorithms (see Section 10.2) may be implemented without a derivation function.. When implemented in this manner, a nonce is not used as shown in Figure 5. Note, however, that the personalization string could contain a nonce, if desired.

The goal of this seed construction is to ensure that the seed is statistically unique.

2. Seed construction for reseeding: The seed material for reseeding consists of three components: one of the current values from the internal state¹, new entropy input and additional input. The internal state value and the entropy input are required; requirements for the entropy input are discussed in item 3. The additional input is optional; requirements for the additional input are discussed in Section 8.5.4. As in item 1, a derivation function may be required for reseeding. See item 1 for further guidance.
3. Entropy requirements for the entropy input: The entropy input for the seed **shall** contain sufficient entropy for the desired level of security. Additional entropy **may** be provided in the nonce or the optional personalization string during instantiation, or in the additional input during reseeding, but this is not required. Entropy

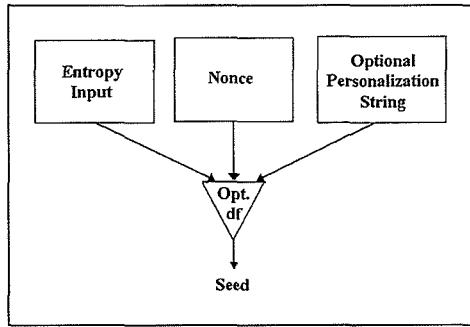


Figure 5: Seed Construction for Instantiation

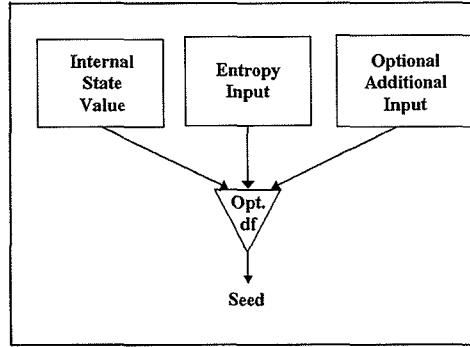


Figure 6: Seed Construction for Reseeding

¹ See each DRBG specification for the value that is used.

contained in the seed components **shall** be distributed across the seed (e.g., by an appropriate derivation function).

The entropy input **shall** have entropy that is equal to or greater than the security strength of the instantiation. Note that the use of more entropy than the minimum value will offer a security “cushion”. This may be useful if the assessment of the entropy provided in the entropy input is incorrect. Having more entropy than the assessed amount is acceptable; having less entropy than the assessed amount could be fatal to security. The presence of more entropy than is required, especially during the instantiation, will provide a higher level of assurance than the minimum required entropy.

4. Seed length: The minimum length of the seed depends on the DRBG and the security strength required by the consuming application. See Section 10.
5. Entropy input source: The source of the entropy input **may** be an Approved NRBG, an Approved DRBG (or chain of Approved DRBGs) that is seeded by an Approved NRBG, or another source whose entropy characteristics are known. Further discussion about the entropy input is provided in Part 4 of this Standard.
6. Entropy input and seed privacy: The entropy input and the resulting seed **shall** be handled in a manner that is consistent with the security required for the data protected by the consuming application. For example, if the DRBG is used to generate keys, then the entropy inputs and seeds used to generate the keys **shall** be treated at least as well as the key.
7. Reseeding: Generating too many outputs from a seed (and other input information) may provide sufficient information for successfully predicting future outputs unless prediction resistance is provided (see Section 8.6). Periodic reseeding will reduce security risks, reducing the likelihood of a compromise of the data that is protected by cryptographic mechanisms that use the DRBG.

Seeds **shall** have a finite seedlife (i.e., the length of the seed period); the maximum seedlife is dependent on the DRBG used. Reseeding is accomplished by 1) an explicit reseeding of the DRBG by the application, or 2) by the generate function when prediction resistance is requested (see Section 8.6) or the limit of the seedlife is reached. An alternative to reseeding is to create an entirely new instantiation.

Reseeding of the DRBG **shall** be performed in accordance with the specification for the given DRBG. The DRBG reseed specifications within this Standard are designed to produce a new seed that is determined by both the old seed and newly-obtained entropy input that will support the desired security strength.

8. Seed use: DRBGs **may** be used to generate both secret and public information. In either case, the seed and the entropy input from which the seed is derived **shall** be kept secret. A single instantiation of a DRBG **should not** be used to generate both secret and public values. However, cost and risk factors must be taken into account when determining whether different instantiations for secret and public values can

be accommodated.

A seed that is used to initialize one instantiation of a DRBG **shall not** be intentionally used to reseed the same instantiation or used as a seed for another DRBG instantiation.

A DRBG **shall not** provide output until a seed is available, and the internal state has been initialized.

9. Seed separation: Seeds used by DRBGs **shall not** be used for other purposes (e.g., domain parameter or prime number generation).

8.5 Other Inputs to the DRBG

8.5.1 Discussion

Other input may be provided during DRBG instantiation, pseudorandom bit generation and reseeding. This input may contain entropy, but this is not required. During instantiation, a personalization string may be provided and combined with entropy input and a nonce to derive a seed (see Section 8.4, item 1). When pseudorandom bits are requested and when reseeding is performed, additional input may be provided (see Section 8.5.4).

Depending on the method for acquiring the input, the exact value of the input may or may not be known to the user or application. For example, the input could be derived directly from values entered by the user or application, or the input could be derived from information introduced by the user or application (e.g., from timing statistics based on key strokes), or the input could be the output of another DRBG or an NRBG.

8.5.2 Nonce

A nonce is required to construct a seed during instantiation. The nonce **shall** be either:

- a. A random value with at least 64 bits of entropy (i.e., a min-entropy of 64 bits),
- b. A non-random value that is guaranteed to never repeat, or
- c. A non-random value that is expected to repeat no more often than a 64-bit random string would be expected to repeat.

For case a, the nonce **may** be acquired from the same source as the entropy input or as part of the entropy input. In this case the seed could be constructed from just the entropy input and the optional personalization string, where the entropy for the entropy input is equal to or greater than security strength + 64 bits.

8.5.3 Personalization String

During instantiation, a personalization string **should** be used to derive the seed (see Section 8.4). The intent of a personalization string is to differentiate this DRBG instantiation from all the others that might ever appear. The personalization string **should** be set to some bitstring that is as unique as possible, and **may** include secret information. The value of any secret information contained in the personalization string **should** be no

greater than the claimed strength of the DRBG, as the DRBG's cryptographic mechanisms (specifically, its backtracking resistance and the entropy provided in the entropy input) will protect this information from disclosure. Good choices for the personalization string contents include:

1. Device serial numbers,
2. Public keys,
3. User identification,
4. Private keys,
5. PINs and passwords,
6. Secret per-module or per-device values,
7. Timestamps,
8. Network addresses,
9. Special secret key values for this specific DRBG instantiation,
10. Application identifiers,
11. Protocol version identifiers,
12. Random numbers, and
13. Nonces.

8.5.4 Additional Input

During each request for bits from a DRBG and during reseeding, the insertion of additional input is allowed. This input is optional and may be either secret or publicly known; its value is arbitrary, although its length may be restricted, depending on the implementation and the DRBG. The use of additional input may be a means of providing more entropy for the DRBG internal state that will increase assurance that the entropy requirements are met. If the additional input is kept secret and has sufficient entropy, the input can provide more assurance when recovering from the compromise of the seed or one or more DRBG internal states.

8.6 Prediction Resistance and Backtracking Resistance

Figure 7 depicts the sequence of DRBG internal states that result from a given seed. Some subset of bits from each internal state are used to generate pseudorandom bits upon request by a user. The following discussions will use the figure to explain backtracking and prediction resistance. Suppose that a compromise occurs at $State_x$, where $State_x$ contains both secret and public information.

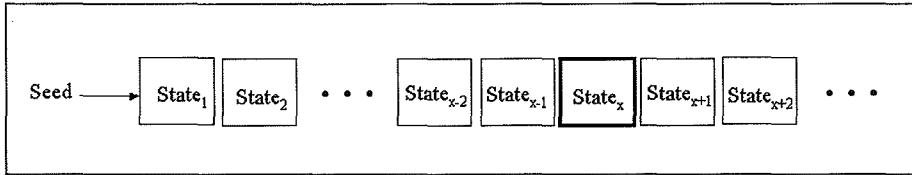


Figure 7: Sequence of DRBG States

Backtracking Resistance: Backtracking resistance means that a compromise of the DRBG internal state has no effect on the security of prior outputs. That is, an adversary who is given access to all of any subset of that prior output sequence cannot distinguish it from random; if the adversary knows only part of the prior output, he cannot determine any bit of that prior output sequence that the adversary ~~he~~ has not already seen. In other words, a compromise has no effect on the security of prior outputs.

For example, suppose that an adversary knows $State_{x-1}$ and also knows the output bits from $State_1$ to $State_{x-2}$. Backtracking resistance means that:

- a. The output bits from $State_1$ to $State_{x-1}$ cannot be distinguished from random.
- a. b. The prior internal state values themselves ($State_1$ to $State_{x-1}$) cannot be recovered, given knowledge of the secret information in $State_x$. $State_x$ and its output bits cannot be determined from knowledge of $State_x$ (i.e., $State_x$ cannot be “backed up”). In addition, since the output bits from $State_1$ to $State_{x-2}$ appear to be random, the output bits for $State_x$ cannot be predicted from the output bits of $State_1$ to $State_{x-2}$.

Formatted: Bullets and Numbering

Formatted

Formatted

Comment [ebb3]: Page: 35
This makes the definition very convoluted.

Backtracking resistance can be provided by :

1. Ensuring that the internal state transition function of a DRBG is a one-way function, or
2. Using the DRBG to generate an additional new DRBG working state before responding to the next request for bits. For example, when bits are generated, the working state is updated; unless the update process uses a one-way function, backtracking resistance is not yet provided. By performing an additional update of the internal state before another request for bits is serviced, backtracking resistance is provided (i.e., the working state is updated twice between requests).

All DRBGs in this Standard have been designed to provide backtracking resistance.

Prediction Resistance: Prediction resistance means that a compromise of the DRBG internal state has no effect on the security of future DRBG outputs. If a compromise of $State_x$ occurs, prediction resistance provides assurance that the output sequence resulting from states after the compromise remains secure. That is, an adversary who is given access

to all of any subset of the output sequence after the compromise cannot distinguish it from random; if the adversary knows only part of the future output sequence, an adversary he cannot predict any bit of that future output sequence that he has not already seen. In other words, a compromise has no effect on the security of future outputs.

For example, suppose that an adversary knows $State_{x_1}$ and also knows the output bits from $State_{x+2}$ to $State_{x+n}$. Prediction resistance means that:

- a. The output bits from $State_{x+1}$ and forward cannot be distinguished from an ideal random bitstring by the adversary.
- b. The future internal state values themselves ($State_{x+1}$ and forward) cannot be predicted, given knowledge of $State_x$, $State_{x+1}$ and its output bits cannot be determined from knowledge of $State_x$ (i.e., $State_x$ cannot be “backed up”). In addition, since the output bits from $State_x$ to $State_{x+1}$ appear to be random, the output bits for $State_{x+1}$ cannot be predicted from the output bits of $State_x$ to $State_{x+1}$.

$State_{x+1}$ and its output bits cannot be predicted from knowledge of $State_x$. In addition, because the output bits from $State_{x+2}$ to $State_{x+n}$ appear to be random, the output bits for $State_{x+1}$ cannot be determined from the output bits of $State_{x+2}$ to $State_{x+n}$.

Formatted: Bullets and Numbering

Formatted

Formatted

Prediction resistance can be provided only by ensuring that a DRBG is effectively reseeded between DRBG requests. That is, an amount of entropy that is sufficient to support the security strength of the DRBG (i.e., an amount that is at least equal to the security strength) must be added to the DRBG in a way that ensures that knowledge of the current^{previous} DRBG internal state does not allow an adversary any useful knowledge about future DRBG internal states or outputs.

9 DRBG Functions

9.1 General Discussion

The DRBG functions in this Standard are specified as an algorithm and an "envelope" of pseudocode around that algorithm. The pseudocode in the envelopes check the input parameters, obtain input not provided by the input parameters, access the appropriate DRBG algorithm and handle the internal state. A function need not be implemented using such envelopes, but the function **shall** have equivalent functionality.

In the specifications of this Standard, the following pseudo-functions are used. These functions are not specifically defined in this Standard, but have the following meaning:

Get_entropy: A function that is used to obtain entropy input. The function call is $(status, entropy_input) = \text{Get_entropy}(\text{security_strength}, \text{min_entropy_input_length}, \text{max_entropy_input_length})$, which requests a string of bits ($entropy_input$) with at least $security_strength$ bits of entropy. The length for the string **shall** be equal to or greater than $min_entropy_input_length$ bits, less than or equal to $max_entropy_input_length$ bits. A $status$ code is also returned from the function.

Block_Encrypt: A basic encryption operation that uses the selected block cipher algorithm. The function call is $output_block = \text{Block_Encrypt}(\text{Key}, \text{input_block})$. For TDEA, the basic encryption operation is called the forward cipher operation; for AES, the basic encryption operation is called the cipher operation. The basic encryption operation is equivalent to an encryption operation on a single block of data using the ECB mode.

9.2 Instantiating a DRBG

A DRBG **shall** be instantiated prior to the generation of pseudorandom bits. The instantiate function **shall**:

1. Check the validity of the input parameters,
2. Determine the security strength for the DRBG instantiation,
3. Determine any DRBG specific parameters (e.g., elliptic curve domain parameters),
4. Obtain entropy input with entropy sufficient to support the security strength,
5. Obtain the nonce,
6. Determine the initial internal state using the instantiate algorithm, and
7. Return a $state_handle$ for the internal state to the consuming application.

Let $working_state$ be the working state for the particular DRBG, and let $min_entropy_input_length$, $max_entropy_input_length$, and $highest_supported_security_strength$ be defined for each DRBG (see Section 10).

The following or an equivalent process **shall** be used to instantiate a DRBG.

Input from a consuming application:

1. *requested_instantiation_security_strength*: A requested security strength for the instantiation. DRBG implementations that support only one security strength do not require this parameter; however, any application using the DRBG must be aware of this limitation.
2. *prediction_resistance_flag*: Indicates whether or not prediction resistance may be required by the consuming application during one or more requests for pseudorandom bits. DRBGs that are implemented to always or never support prediction resistance do not require this parameter. However, the user of a consuming application must determine whether or not prediction resistance may be required by the application before electing to use such a DRBG implementation. If the *prediction_resistance_flag* is not needed (i.e., because prediction resistance is always or never performed), then the input parameter and step 2 may be omitted, and the *prediction_resistance_flag* may be omitted from the internal state in step 11.
3. *personalization_string*: An optional input that provides personalization information (see Sections 8.4 and 8.5.3). The maximum length of the personalization string (*max_personalization_string_length*) is implementation dependent, but **shall** be $\leq 2^{35}$ bits. If a personalization string will never be used, then the input parameter and step 3 may be omitted, and step 9 may be modified to remove the personalization string.
5. *DRBG_specific_input_parameters* : Any additional parameters that are allowed for a specific DRBG (see Section 10). The use of the DRBG-specific input parameters is discussed for the DRBG instantiate algorithms. If a DRBG or a DRBG implementation does not use these parameters, then step 5 may be omitted.

Required information not provided by the consuming application:

Comment: This input **shall not** be provided by the consuming application as an input parameter during the instantiate request.

1. *entropy_input*: Input bits containing entropy. The maximum length of the *entropy_input* is implementation dependent, but **shall** be $\leq 2^{35}$ bits.
2. *nonce*: A nonce as specified in Section 8.5.2. Note that in certain circumstances, the nonce will not be used. In this case, step 8 **shall** be omitted, and the nonce parameter **shall** be removed from step 9.

Output to a consuming application:

1. *status*: The status returned from the instantiate function. The *status* will indicate **SUCCESS** or an **ERROR**. If an **ERROR** is indicated, either no *state_handle* or an

invalid *state_handle* shall be returned. A consuming application **should** check the *status* to determine that the DRBG has been correctly instantiated.

2. *state_handle*: Used to identify the internal state for this instantiation in subsequent calls to the generate, reseed, uninstantiate and test functions.

Information retained within the DRBG boundary:

The internal state for the DRBG, including the *working_state*, *security_strength*, and *prediction_resistance_flag* (see Section 10).

Process:

Comment: Check the validity of the input parameters.

1. If *requested_instantiation_security_strength* > *highest_supported_security_strength*, then return an **ERROR**.
2. If *prediction_resistance_flag* is set, and prediction resistance is not supported, then return an **ERROR**.
3. If the length of the *personalization_string* > *max_personalization_string_length*, return an **ERROR**.
4. Set *security_strength* to the nearest security strength greater than or equal to *requested_instantiation_security_strength*.

Comment: The following step is required by the Dual_EC_DRBG when multiple curves are available (see Section 10.3.2.2.2), and by the MS_DRBG (see Section 10.3.3.2.3). Otherwise, the step should be omitted.

5. Using *security_strength* and *DRBG_specific_input_parameters* (if available), select appropriate DRBG parameters.

Comment: Determine the minimum entropy requirement and obtain the entropy input.

6. (*status*, *entropy_input*) = **Get_entropy** (*security_strength*, *min_entropy_input_length*, *maximum_entropy_input_length*).
7. If an **ERROR** is returned in step 6, return an **ERROR**.
8. Obtain a *nonce*.

Comment: This step shall include any appropriate checks on the acceptability of the *nonce*. See Section 8.5.2.

Comment: Call the appropriate instantiate algorithm in Section 10 to obtain values for the initial *working_state* using the *entropy_input*, the *nonce*, the

personalization_string (if provided) and other parameters (as required).

9. *working_state* = **Instantiate_algorithm** (*entropy_input*, *nonce*, *personalization_string*, other DRBG parameters).

Comment: Set up the initial internal state.

10. Get a *state_handle* that will be used to locate the internal state for this instantiation.
If an unused internal state cannot be found, return an **ERROR**.
11. Set the internal state indicated by *state_handle* to the initial values: *working_state*, *security_strength*, and *prediction_resistance_flag*, as appropriate.
12. Return **SUCCESS** and *state_handle*.

9.3 Reseeding a DRBG Instantiation

The reseeding of an instantiation is not required, but is recommended whenever an application and implementation are able to perform this process. Reseeding will insert additional entropy into the generation of pseudorandom bits. Reseeding may be:

- explicitly requested by an application,
- performed when prediction resistance is requested by an application,
- triggered by the generate function when a predetermined number of pseudorandom outputs have been produced (i.e., at the end of the seedlife), or
- triggered by external events (e.g., whenever sufficient entropy is available).

If a reseed capability is not available, a new DRBG instantiation may be created (see Section 9.2).

The reseed function **shall**:

1. Check the validity of the input parameters,
2. Obtain entropy input with entropy sufficient to support the security strength, and
3. Using the reseed algorithm, combine the current working state with the new entropy input and any additional input to determine the new working state.

Let *working_state* be the working state for the particular DRBG, and let *min_entropy_input_length* and *max_entropy_input_length* be defined for each DRBG (see Section 10).

The following or an equivalent process **shall** be used to reseed the DRBG instantiation.

Input from a consuming application:

- 1) *state_handle*: A pointer or index that indicates the internal state to be reseeded.
This value was returned from the instantiate function specified in Section 9.2.

- 2) *additional_input*: An optional input. The maximum length of the *additional_input* (*max_additional_input_length*) is implementation dependent, but **shall** be $\leq 2^{35}$ bits. If *additional_input* will never be used, then the input parameter and step 2 may be omitted, and step 5 may be modified to remove the *additional_input*.

Required information not provided by the consuming application:

Comment: This input **shall not** be provided by the consuming application in the input parameters.

1. *entropy_input*: Input bits containing entropy. The maximum length of the *entropy_input* is implementation dependent, but **shall** be $\leq 2^{35}$ bits.
2. Internal state values required by the DRBG for reseeding, including the *working_state*, *security_strength* and *prediction_resistance_flag*, as appropriate.

Output to a consuming application:

1. *status*: The status returned from the function. The *status* will indicate **SUCCESS** or an **ERROR**.

Information retained within the DRBG boundary:

Replaced internal state values (i.e., the *working_state*).

Process:

Comment: Get the current internal state and check the input parameters.

1. Using *state_handle*, obtain the current internal state. If *state_handle* indicates an invalid or unused internal state, return an **ERROR**.
2. If the length of the *additional_input* > *max_additional_input_length*, return an **ERROR**.

Comment: Determine the minimum entropy requirement and obtain the entropy input.

3. $(status, entropy_input) = \text{Get_entropy} (security_strength, min_entropy_input_length, max_entropy_input_length)$.
4. If an **ERROR** is returned in step 4, return an **ERROR**.

Comment: Get the new *working_state* using the appropriate reseed algorithm in Section 10.

5. $(status, working_state) = \text{Reseed_algorithm} (working_state, entropy_input, additional_input)$.

Comment: Save the new values of the internal

state.

6. Replace the *working_state* in the internal state indicated by *state_handle* with the new values.
7. Return SUCCESS.

9.4 Generating Pseudorandom Bits Using a DRBG

This function is used to generate pseudorandom bits after instantiation or reseeding (see Sections 9.2 and 9.3). The generate function **shall**:

1. Check the validity of the input parameters,
2. If the instantiation needs additional entropy because the end of the seedlife has been reached or prediction resistance is required, call the reseed function to obtain sufficient entropy.
3. Generate the requested pseudorandom bits using the generate algorithm.
4. Update the working state.
5. Return the requested pseudorandom bits to the consuming application.

Let *outlen* be the length of the output block of the cryptographic primitive (see Section 10).

The following or an equivalent process **shall** be used to generate pseudorandom bits.

Input from a consuming application:

1. *state_handle*: A pointer or index that indicates the internal state to be used.
2. *requested_number_of_bits*: The number of pseudorandom bits to be returned from the generate function. The *max_number_of_bits_per_request* is defined for each DRBG in Section 10.
3. *requested_security_strength*: The security strength to be associated with the requested pseudorandom bits. DRBG implementations that support only one security strength do not require this parameter; however, any application using the DRBG must be aware of this limitation.
4. *prediction_resistance_request*: Indicates whether or not prediction resistance is to be provided prior to the generation of the requested pseudorandom bits to be generated. DRBGs that are implemented to always or never support prediction resistance do not require this parameter. However, the user of a consuming application must determine whether or not prediction resistance may be required by the application before electing to use such a DRBG implementation. If the *prediction_resistance_request* parameter is not needed, then the input parameter and step 5 may be omitted ; in addition, step 7 may be modified to remove the check for the *prediction_resistance_request*.
5. *additional_input*: An optional input. The maximum length of the *additional_input* (*max_additional_input_length*) is implementation dependent, but **shall** be $\leq 2^{35}$

bits. If *additional_input* will never be used, then the input parameter, step 4, step 7.4 and the *additional_input* input parameter in step 8 may be omitted.

Required information not provided by the consuming application:

1. Internal state values required for generation, including the *working_state*, *security_strength* and *prediction_resistance_flag*, as appropriate.

Output to a consuming application:

1. *status*: The status returned from the function. The *status* will indicate **SUCCESS** or an **ERROR**.
2. *pseudorandom_bits*: The pseudorandom bits that were requested.

Information retained within the DRBG boundary:

Replaced internal state values (i.e., the *working_state*).

Process:

Comment Get the internal state and check the input parameters.

1. Using *state_handle*, obtain the current internal state for the instantiation. If *state_handle* indicates an invalid or unused internal state, then return an **ERROR**.
2. If *requested_number_of_bits* > *max_number_of_bits_per_request*, then return an **ERROR**.
3. If *requested_security_strength* > the *security_strength* indicated in the internal state, then return an **ERROR**.
4. If the length of the *additional_input* > *max_additional_input_length*, then return an **ERROR**.
5. If *prediction_resistance_request* is set, and *prediction_resistance_flag* is not set, then return an **ERROR**.
6. Reset the *reseed_required_flag*.

Comment: Get the requested pseudorandom bits.

7. If *reseed_required_flag* is set, or if *prediction_resistance_request* is set, then

Comment: Reseed the instantiation (see Section 9.3).

- 7.1 *status* = **Reseed** (*state_handle*, *additional_input*).
- 7.2 If *status* indicates an **ERROR**, then return **ERROR**.
- 7.3 Using *state_handle*, obtain the new internal state.
- 7.4 *additional_input* = the *Null* string.

7.5 Reset the *reseed_required_flag*.

Comment: Request the generation of *pseudorandom_bits* using the appropriate generate algorithm in Section 10.

8. $(status, pseudorandom_bits, working_state) = \text{Generate_algorithm}(working_state, requested_number_of_bits, additional_input)$.
9. If *status* indicates that a reseed is required before the requested bits can be generated, then
 - 9.1 Set the *reseed_required_flag*.
 - 9.2 Go to step 7.
10. Replace the old *working_state* in the internal state indicated by *state_handle* with the new *working_state*.
11. Return **SUCCESS** and *pseudorandom_bits*.

Implementation notes:

If a reseed capability is not available, then steps 6 and 7 may be omitted; replace step 8 by:

Using the *working_state* in the internal state, any *additional_input* and the value of *requested_number_of_bits*, obtain *pseudorandom_bits* and the new *working_state* from the DRBG generate algorithm. If a reseed is required before the requested bits can be generated, then return an indication that the DRBG instantiation can no longer be used.

9.5 Removing a DRBG Instantiation

The internal state for an instantiation may need to be “released”. This may be required, for example, following health testing of the instantiation function. The uninstantiate function **shall**:

1. Check the input parameter for validity.
2. Empty the internal state.

The following or an equivalent process **shall** be used to remove (i.e., uninstantiate) a DRBG instantiation:

Input from a consuming application:

1. *state_handle*: A pointer or index that indicates the internal state to be “released”.

Output to a consuming application:

1. *status*: The status returned from the function. The status will indicate **SUCCESS** or **FAILURE**.

Information retained within the DRBG boundary:

An empty internal state.

Process:

1. If *state_handle* indicates an invalid state, then return **FAILURE**.
2. Erase the contents of the internal state indicated by *state_handle*.
3. Return **SUCCESS**.

9.6 Auxilliary Functions

9.6.1 Introduction

Derivation functions are internal functions that are used during DRBG instantiation and reseeding to either derive internal state values or to distribute entropy throughout a bitstring. Two methods are provided. One method is based on hash functions (see Section 9.6.2), and the other method is based on block cipher algorithms (see 9.6.3). The block cipher derivation function uses a a CBC_MAC that is specified in Section 9.6.4.

9.6.2 Derivation Function Using a Hash Function (Hash_df)

The hash-based derivation function hashes an input string and returns the requested number of bits. Let **Hash** (...) be the hash function used by the DRBG, and let *outlen* be its output length.

The following or an equivalent process **shall** be used to derive the requested number of bits.

Input:

1. *input_string*: The string to be hashed.
2. *no_of_bits_to_return*: The number of bits to be returned by **Hash_df**. The maximum length (*max_number_of_bits*) is implementation dependent, but **shall** be $\leq (255 \times \text{outlen})$. *no_of_bits_to_return* is represented as a 32-bit integer.

Output:

1. *status*: The status returned from **Hash_df**. The status will indicate **SUCCESS** or **ERROR**.
2. *requested_bits* : The result of performing the **Hash_df**.

Process:

1. If *no_of_bits_to_return* > *max_number_of_bits*, then return an **ERROR**.
2. *temp* = the Null string.
3.
$$\text{len} = \left\lceil \frac{\text{no_of_bits_to_return}}{\text{outlen}} \right\rceil.$$

4. *counter* = a 32-bit binary value representing the integer "1".
5. For $i = 1$ to *len* do
 - 5.1 $\text{temp} = \text{temp} \parallel \text{Hash}(\text{counter} \parallel \text{no_of_bits_to_return} \parallel \text{input_string})$.
 - 5.2 $\text{counter} = \text{counter} + 1$.
6. *requested_bits* = Leftmost (*no_of_bits_to_return*) of *temp*.
7. Return **SUCCESS** and *requested_bits*.

9.6.3 Derivation Function Using a Block Cipher Algorithm

Let **Block_Cipher_Hash** be the function specified in Section 9.6.4. Let *outlen* be its output block length, and let *keylen* be the key length.

The following or an equivalent process **shall** be used to derive the requested number of bits.

Input:

1. *input_string*: The string to be operated on. This string **shall** be a multiple of 8 bits.
2. *no_of_bits_to_return*: The number of bits to be returned by **Block_Cipher_df**. The maximum length (*max_number_of_bits*) is 512 bits for the currently approved block cipher algorithms.

Output:

1. *status*: The status returned from **Block_Cipher_df**. The status will indicate **SUCCESS** or **ERROR**.
2. *requested_bits* : The result of performing the **Block_Cipher_df**.

Process:

1. If (*number_of_bits_to_return* > *max_number_of_bits*), then return an **ERROR**.
2. $L = \text{len}(\text{input_string})/8$. Comment: L is the bitstring representation of the integer resulting from $\text{len}(\text{input_string})/8$. L **shall** be represented as a 32-bit integer.
3. $N = \text{number_of_bits_to_return}/8$. Comment : N is the bitstring representation of the integer resulting from *number_of_bits_to_return*/8. N **shall** be represented as a 32-bit integer.
Comment: Prepend the string length and the requested length of the output to the *input_string*.
3. $S = L \parallel N \parallel \text{input_string} \parallel 0x80$.

- Comment : Pad S with zeros, if necessary.
4. While $(\text{len}(S) \bmod \text{outlen}) \neq 0$, $S = S \parallel 0x00$.
Comment : Compute the starting value.
 5. $\text{temp} =$ the *Null* string.
 6. $i = 0$.
Comment : i shall be represented as a 32-bit integer.
 7. $K =$ Leftmost keylen bits of $0x010203\dots1F$.
 8. While $\text{len}(\text{temp}) < \text{keylen} + \text{outlen}$, do
 - 8.1 $IV = i \parallel 0^{\text{outlen} - \text{len}(i)}$.
Comment: The integer representation of i is padded with zeros to outlen bits.
 - 8.2 $\text{temp} = \text{temp} \parallel \text{Block_Cipher_Hash}(K, (IV \parallel S))$.
 - 8.3 $i = i + 1$.
Comment: Compute the requested number of bits.
 9. $K =$ Leftmost keylen bits of temp .
 10. $X =$ Next outlen bits of temp .
 11. $\text{temp} =$ the *Null* string.
 12. While $\text{len}(\text{temp}) < \text{number_of_bits_to_return}$, do
 - 12.1 $X = \text{Block_Encrypt}(K, X)$.
 - 12.2 $\text{temp} = \text{temp} \parallel X$.
 13. $\text{requested_bits} =$ Leftmost $\text{number_of_bits_to_return}$ of temp .
 14. Return **SUCCESS** and requested_bits .

9.6.4 Block_Cipher_Hash Function

Let outlen be the length of the output block of the block cipher algorithm to be used.

The following or an equivalent process shall be used to derive the requested number of bits.

Input:

1. *Key*: The key to be used for the block cipher operation.
2. *data_to_hash*: The data to be operated upon. Note that the length of *data_to_hash* must be a multiple of outlen . This is guaranteed by steps 4 and 8.1 in Section 9.6.3.

Output:

1. *output_block*: The result to be returned from the **Block_Cipher_Hash** operation.

Process:

1. *chaining_value* = 0^{outlen} . Comment: Set the first chaining value to *outlen* zeros.
2. *n* = *len* (*data_to_hash*) / *outlen*.
3. Split the *data_to_hash* into *n* blocks of *outlen* bits each forming *block*₁ to *block*_{*n*}.
4. For *i* = 1 to *n* do
 - 4.1 *input_block* = *chaining_value* \oplus *block*_{*i*}.
 - 4.2 *chaining_value* = **Block_Encrypt** (*Key*, *input_block*).
5. *output_block* = *chaining_value*.
6. Return *output_block*.

9.7 Self-Testing of the DRBG

9.7.1 Discussion

A DRBG **shall** perform self testing to obtain assurance that the implementation continues to operate as designed and implemented (health testing). The testing function within a DRBG boundary (or sub-boundary) **shall** test all DRBG functions within that boundary. Four function configurations are possible within a single DRBG boundary or sub-boundary:

1. Instantiate, generate, uninstantiate and test functions,
2. Generate and test functions,
3. Reseed, generate and test functions,
4. Instantiate, generate, reseed, uninstantiate and test functions.

DRBG health testing **shall** be performed prior to the first instantiation of the DRBG, at periodic intervals and on-demand. Bits generated during health testing **shall not** be output as pseudorandom bits.

Implementations may differ on the meaning of periodic testing. For implementations that have continuous power, periodic testing is performed, for example, every hour or every day or every time the DRBG is accessed. For implementations that do not have continuous power (e.g., power is available for only short periods of time), periodic testing is performed at power-up.

Two levels of DRBG health testing are allowed: 1) extensive tests² that are conducted when sufficient time is available, and 2) minimal tests that are conducted when little time is available for testing. Table 2 summarizes when extensive versus minimal DRBG health testing is performed. All DRBG implementations **shall** conform to one of the three cases listed in the table. When testing is performed on-demand, extensive testing **shall** always be

² This is not intended to be as extensive as implementation validation tests; see Section 11.

ANS X9.82, Part 3 - DRAFT - March 2005

conducted. For testing performed prior to the first instantiation or periodically, extensive testing **shall** be conducted either 1) prior to the first instantiation (case 1), or 2) **shall** be conducted periodically (case 2), or 3) **shall** be conducted both prior to the first instantiation and periodically (case 3). In all cases, a configuration for a function **shall not** be used operationally until it has been tested.

Table 1 : Health Testing Intervals and Levels of Testing

	Prior to first instantiation	Periodic	On-Demand
Case 1	Extensive	Minimal	Extensive
Case 2	Minimal	Extensive	Extensive
Case 3	Extensive	Extensive	Extensive

In general, each of the DRBG functions **shall** be tested as follows:

1. Instantiate function: Fixed values for the entropy input **shall** be used during testing; the fixed values **shall not** be used during normal operations.

Extensive testing: Each possible configuration of *security_strength*, *prediction_resistance_flag* and *DRBG_specific_input_parameters* **shall** be tested (depending on which input parameters are implemented). Representative values and lengths of the *personalization_string* **shall** be used. In addition, the error handling for each input parameter and for an error in obtaining the *entropy_input* **shall** be tested (e.g., the *entropy_input* source is broken).

Minimal testing: A minimal test **shall** include a single *security_strength*; a single set of *DRBG_specific_input_parameters*; a single representative value for the *personalization_string* (depending on which parameters are implemented); if prediction resistance is possible, this capability **shall** also be tested. If the combination of *security_strength* and *DRBG_specific_input_parameters* passes the health test, then this combination of parameters may be used operationally by the instantiate function. If minimal testing is performed prior to the first instantiation, the error handling for each input parameter and for an error in obtaining the *entropy_input* **shall** be tested (e.g., the *entropy_input* source is broken).

2. Generate function: Known values for the internal state **shall** be used.

Extensive testing: Each possible configuration of *requested_security_strength* and *prediction_resistance_request* **shall** be tested (depending on the input parameters that are implemented); representative values and lengths for *requested_number_of_bits* and *additional_input* (if allowed) **shall** be used. Testing **shall** include setting the *reseed_counter* to meet or exceed the *reseed_interval* in order to check that the implementation is reseeded or that the DRBG is “shut down”. In addition, the error handling for each input parameter **shall** be tested.

Minimal testing: A minimal test **shall** include a single value for the

requested_security_strength and single representative values for the *requested_number_of_bits* and *additional_input* (depending on which parameters are implemented); if the *prediction_resistance_request* input parameter is available, a request for prediction resistance **shall** be tested. If the combination of *requested_security_strength* and *prediction_resistance_request* (if appropriate) passes the health test, then this combination of parameters may be used operationally by the generate function. If minimal testing is performed prior to the first instantiation, and if the *requested_security_strength* input parameter is used, a test of the error handling for an invalid *requested_security_strength* **shall** be conducted.

3. Reseed function: Fixed values for the entropy input **shall** be used during testing; the fixed values **shall not** be used during normal operations.

Extensive testing: Internal states with all possible configurations of *security_strength* and *prediction_resistance_flag* **shall** be tested (depending on the input parameters that are implemented); representative values of *additional_input* **shall** be used if additional input can be provided. In addition, the error handling for each input parameter and for an error in the *entropy_input* **shall** be tested (e.g., the *entropy_input* source is broken).

Minimal testing: A minimal test **shall** include the test of a single *security_strength* and *prediction_resistance_flag* (if appropriate), and a representative *additional_input* (if allowed). If the combination of *security_strength* and *prediction_resistance_flag* (if appropriate) passes the health test, then this combination of parameters may be used operationally by the reseed function. If minimal testing is performed prior to the first instantiation, the error handling for each input parameter and for an error in the *entropy_input* **shall** be tested (e.g., the *entropy_input* source is broken).

4. Uninstantiate function: Check the error handling for an invalid *state_handle*, as a minimum. If possible, check that the internal state has been "emptied".

Errors occurring during testing **shall** be perceived as complete DRBG failures. The condition causing the failure **shall** be corrected and the DRBG re-instantiated before requesting pseudorandom bits (also see Section 9.8).

9.7.2 Instantiate, Generate, Uninstantiate and Test Functions

As specified in Section 8.3, any DRBG boundary (or sub-boundary) that includes an instantiate function **shall** also include uninstantiate, generate and testing functions within that boundary. Note that this configuration does not include a reseed function. The testing function **shall**:

1. Select a combination of valid instantiate and generate input parameters and an appropriate fixed value for the *entropy_input*. Note that for minimal testing, only one combination of instantiate and generate parameters would be used.

2. Request an instantiation using a valid set of instantiate input parameters, obtaining the (fixed) *entropy_input*, setting the internal state and returning a *state_handle* for the internal state.
3. Using the *state_handle*, request the generation of pseudorandom bits using a valid set of generate input parameters.
4. Check that the generated pseudorandom bits match expected values. If the generated and expected values do not match, the test fails; abort the test.
5. Repeat from step 1 until all valid combinations have been tested.
6. Test the error handling for the instantiate, generate and uninstantiate functions (as appropriate, see Section 9.7.1). If any of the functions do not handle error handling correctly, abort the test.
7. Uninstantiate the internal state used for testing.

If the test was not aborted, each combination of input parameters that was selected in step 1 may be used operationally.

9.7.3 Generate and Test within a Single DRBG Sub-boundary

As specified in Section 8.3, any DRBG boundary or sub-boundary that includes a generate function **shall** also include a testing function. Note that this configuration does not comprise a complete DRBG, since the instantiate and uninstantiate functions are not present. The testing function **shall**:

1. Select a combination of valid generate input parameters to be used and an appropriate fixed value for the internal state. Note that for minimal testing, only one combination generate parameters would be used
2. Using a *state_handle* for the selected internal state, request the generation of pseudorandom bits.
3. Check that the generated pseudorandom bits match expected values. If the generated and expected values do not match, the test fails; abort the test.
4. Repeat from step 1 until all valid combinations have been tested.
5. Test the error handling for the generate function (as appropriate, see Section 9.7.1). If any of the functions do not handle error handling correctly, abort the test.

If the test was not aborted, each combination of input parameters that was selected in step 1 may be used operationally.

9.7.4 Reseed, Generate and Test within a Single DRBG Sub-boundary

As specified in Section 8.3, any DRBG boundary or sub-boundary that includes a reseed function **shall** include generate and testing functions. Note that this configuration does not comprise a complete DRBG, since the instantiate and uninstantiate functions are not

present. The testing function **shall**:

1. Select a combination of valid reseed and generate input parameters, an appropriate fixed value for the internal state, and an appropriate fixed value for the *entropy_input*. Note that for minimal testing, only one combination of reseed and generate parameters would be used
2. Using a *state_handle* for the selected internal state, request a reseed of the instantiation using a valid set of reseed input parameters, obtaining the *entropy_input*, and setting the new value of the internal state.
3. Using the *state_handle*, request the generation of pseudorandom bits using a valid set of generate input parameters.
4. Check that the generated pseudorandom bits match expected values. If the generated and expected values do not match, the test fails; abort the test.
5. Repeat from step 1 until all valid combinations have been tested.
6. Test the error handling for the reseed and generate functions (as appropriate, see Section 9.7.1). If any of the functions do not handle error handling correctly, abort the test.

If the test was not aborted, each combination of input parameters that was selected in step 1 may be used operationally.

9.7.5 Instantiate, Uninstantiate, Generate, Reseed and Test Functions

This configuration contains all DRBG functions within the same device. The testing function for a DRBG boundary that includes all DRBG functions **shall**:

1. Select a combination of valid instantiate, generate and reseed input parameters, and appropriate fixed values for the *entropy_input* for both the instantiate and reseed functions. Note that for minimal testing, only one combination of instantiate, generate and reseed parameters would be used
2. Request an instantiation using a valid set of instantiate input parameters, obtaining the (fixed) *entropy_input*, setting the internal state and returning a *state_handle* for the internal state.
3. Using the *state_handle*, request the generation of pseudorandom bits using a valid set of generate input parameters. If prediction resistance is requested, a fixed value for the entropy input **shall** be used.
4. Using a *state_handle*, request a reseed of the instantiation using a valid set of reseed input parameters, obtaining the (fixed) *entropy_input*, and setting the new value of the internal state.
5. Using the *state_handle*, request the generation of pseudorandom bits using a valid set of generate input parameters. If prediction resistance is requested, a fixed value for the entropy input **shall** be used.

6. Check that the generated pseudorandom bits match expected values. If the generated and expected values do not match, the test fails: abort the test.
7. Repeat from step 1 until all valid combinations have been tested.
8. Test the error handling for the instantiate, generate, reseed and uninstantiate functions (as appropriate, see Section 9.7.1). If any of the functions do not handle error handling correctly, abort the test.
9. Uninstantiate the internal state used for testing.

If the test was not aborted, each combination of input parameters that was selected in step 1 may be used operationally.

9.8 Error Handling

The expected errors are indicated for each DRBG function (see Sections 9.2 - 9.5) and for the derivation functions in Section 9.6. The error handling routines **should** indicate the type of error. For catastrophic errors (e.g., entropy input source failure), the DRBG **shall not** produce further output until the source of the error is corrected.

Many errors during normal operation may be caused by an application's improper DRBG request. In these cases, the application user is responsible for correcting the request within the limits of the user's organizational security policy. For example, if a failure indicating an invalid requested security strength is returned, a security strength higher than the DRBG or the DRBG instantiation can support has been requested. The user **may** reduce the requested security strength if the organization's security policy allows the information to be protected using a lower security strength, or the user **shall** use an appropriately instantiated DRBG.

Failures that indicate that the entropy source has failed or that the DRBG failed health testing (see Sections 9.7 and 11.4) **shall** be handled as complete DRBG failures. The indicated DRBG problem **shall** be corrected, and the DRBG **shall** be re-instantiated before the DRBG can be used to produce pseudorandom bits.

10 DRBG Algorithm Specifications

Several DRBGs are specified in this Standard. The selection of a DRBG depends on several factors, including the security strength to be supported and what cryptographic primitives are available. An analysis of the consuming application's requirements for random numbers **shall** be conducted in order to select an appropriate DRBG. A detailed discussion on DRBG selection is provided in Annex E. Pseudocode examples for each DRBG are provided in Annex F. Conversion specifications required for the DRBG implementations (e.g., between integers and bitstrings) are provided in Annex B.

10.1 Deterministic RBGs Based on Hash Functions

10.1.1 Discussion

A hash DRBG is based on a hash function that is non-invertible or one-way. The hash DRBGs specified in this Standard have been designed to use any Approved hash function and may be used by applications requiring various security strengths, providing that the appropriate hash function is used and sufficient entropy is obtained for the seed. The following are provided as DRBGs based on hash functions:

1. The **Hash_DRBG** specified in Section 10.1.2.
2. The **HMAC_DRBG** specified in Section 10.1.3.

The maximum security strength that could be supported by each hash function when used in a DRBG is equal to the number of bits in the hash function output block. However, this Standard supports only four security strengths: 112, 128, 192, and 256. Table 3 specifies the values that **shall** be used for the function envelopes and DRBG algorithm for each Approved hash function. The specifications in this Standard assume that a single appropriate hash function will be selected for a DRBG implementation; i.e., a DRBG implementation will not contain multiple hash functions from which to choose during instantiation.

Table 3: Definitions for Hash-Based DRBGs

	SHA-1	SHA-224	SHA-256	SHA-384	SHA-512
Supported security strengths	112, 128	112, 128, 192	112, 128, 192, 256	112, 128, 192, 256	112, 128, 192, 256
highest_supported_security_strength	128	192	256	256	256
Output Block Length (outlen)	160	224	256	384	512
Required minimum entropy for instantiate and reseed	<i>security_strength</i>				
Minimum entropy input length (min_entropy_input_length)	<i>security_strength</i>				

	SHA-1	SHA-224	SHA-256	SHA-384	SHA-512
Maximum entropy input length (max_entropy_input_length)	$\leq 2^{35}$ bits				
Seed length (seedlen) for Hash_DRBG	440	440	440	888	888
Maximum personalization string length (max_personalization_string_length)	$\leq 2^{35}$ bits				
Maximum additional_input length (max_additional_input_length)	$\leq 2^{35}$ bits				
max_number_of_bits_per_request	$\leq 2^{19}$ bits				
Number of requests between reseeds (reseed_interval)	$\leq 2^{48}$				

Note that since SHA-224 is based on SHA-256, there is no efficiency benefit for using the smaller hash function; this is also the case for SHA-384 and SHA-512, i.e., the use of SHA-256 or SHA-512 instead of SHA-224 or SHA-384, respectively, is preferred. The value for *seedlen* is determined by subtracting the count field and one byte of padding from the hash function input block length; In the case of SHA-1, SHA-224 and SHA 256, *seedlen* = 512 - 64 - 8 = 440; for SHA-384 and SHA-512, *seedlen* = 1024 - 128 - 8 = 888.

10.1.2 Hash_DRBG

10.1.2.1 Discussion

Figure 8 presents the normal operation of the Hash_DRBG. The Hash_DRBG requires the use of a hash function during the instantiate, reseed and generate functions; the same hash function **shall** be used in all functions. The hash function to be used **shall** meet or exceed the desired security strength of the consuming application.

Implementation validation testing and health testing are discussed in Sections 9.7 and 11.

10.1.2.2 Specifications

10.1.2.2.1 Hash_DRBG Internal State

The *internal_state* for Hash_DRBG consists of:

1. The *working_state*:
 - a. A value (*V*) of *seedlen* bits that is updated during each call to the DRBG.
 - b. A constant *C* of *seedle* bits that depends on the *seed*.
 - c. A counter (*reseed_counter*) that indicates the number of requests for

pseudorandom bits since new *entropy_input* was obtained during instantiation or reseeding.

2. Administrative information:

- a. The *security_strength* of the DRBG instantiation.
- b. A *prediction_resistance_flag* that indicates whether or not a prediction resistance capability is required for the DRBG.

The values of *V* and *C* are the critical values of the internal state upon which the security of this DRBG depends (i.e., *V* and *C* are the “secret values” of the internal state).

10.1.2.2.2 Instantiation of Hash_DRBG

Notes for the instantiate function:

The instantiation of **Hash_DRBG** requires a call to the instantiate function specified in Section 9.2; step 9 of that function calls the instantiate algorithm in this section. For this DRBG, no *DRBG_specific_input_parameters* are required for the instantiate function specified in Section 9.2 (i.e., step 5 **should** be omitted).

The values of *highest_supported_security_strength* and *min_entropy_input_length* are provided in Table 3 of Section

10.1.1. The contents of the internal state are provided in Section 10.1.2.2.1.

The instantiate algorithm:

Let **Hash_df** be the hash derivation function specified in Section 9.6.2 using the selected hash function. The output block length (*outlen*), seed length (*seedlen*) and appropriate *security_strengths* for the implemented hash function are provided in Table 3 of Section 10.1.1.

The following process or its equivalent **shall** be used as the instantiate algorithm for

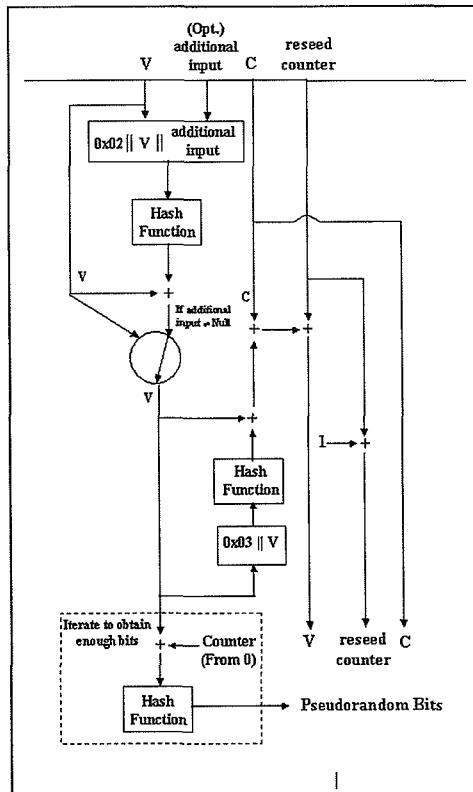


Figure 8: Hash_DRBG

this DRBG (see step 9 in Section 9.2).

Input:

1. *entropy_input*: The string of bits obtained from the entropy input source.
2. *nonce*: A string of bits as specified in Section 8.5.2.
3. *personalization_string*: The personalization string received from the consuming application. If a *personalization_string* will never be used, then steps 1 and 2 may be combined as follows:

$$\text{seed} = \text{Hash_df}(\text{entropy_input}, \text{seedlen}).$$

Output:

1. *working_state*: The initial values for *V*, *C* and *reseed_counter* (see Section 10.1.2.2.1).

Process:

1. *seed_material* = *entropy_input* || *nonce* || *personalization_string*.
2. *seed* = **Hash_df**(*seed_material*, *seedlen*).
3. *V* = *seed*.
4. *C* = **Hash_df**((0x00 || *V*), *seedlen*). Comment: Precede *V* with a byte of zeroes.
5. *reseed_counter* = 1.
6. Return *V*, *C* and *reseed_counter* as the *working_state*.

10.1.2.2.3 Reseeding a Hash_DRBG Instantiation

Notes for the reseed function:

The reseeding of a **Hash_DRBG** instantiation requires a call to the **reseed** function specified in Section 9.3; step 5 of that function calls the reseed algorithm specified in this section. The values for *min_entropy_input_length* are provided in Table 3 of Section 10.1.1.

The reseed algorithm:

Let **Hash_df** be the hash derivation function specified in Section 9.6.2 using the selected hash function. The value for *seedlen* is provided in Table 3 of Section 10.1.1.

The following process or its equivalent shall be used as the reseed algorithm for this DRBG (see step 5 in Section 9.3):

Input:

1. *working_state*: The current values for *V*, *C* and *reseed_counter* (see Section 10.1.2.2.1).

2. *entropy_input*: The string of bits obtained from the entropy input source.
3. *additional_input*: The additional input string received from the consuming application. If *additional_input* will never be provided, then step 1 may be modified to remove the *additional_input*.

Output:

1. *working_state*: The new values for *V*, *C* and *reseed counter*.

Process:

1. *seed_material* = $0x01 \parallel V \parallel \text{entropy_input} \parallel \text{additional_input}$.
2. *seed* = **Hash_df** (*seed_material*, *seedlen*).
3. *V* = *seed*.
4. *C* = **Hash_df** ($(0x00 \parallel V)$, *seedlen*). Comment: Precede with a byte of all zeros.
5. *reseed_counter* = 1.
6. Return *V*, *C* and *reseed_counter* as the new *working_state*.

10.1.2.2.4 Generating Pseudorandom Bits Using Hash_DRBG

Notes for the generate function:

The generation of pseudorandom bits using a **Hash_DRBG** instantiation requires a call to the generate function specified in Section 9.4; step 8 of that function calls the generate algorithm specified in this section. The values for *max_number_of_bits_per_request* and *outlen* are provided in Table 3 of Section 10.1.1.

The generate algorithm:

Let **Hash** be the selected hash function. The seed length (*seedlen*) and the maximum interval between reseeding (*reseed_interval*) are provided in Table 3 of Section 10.1.1. Note that for this DRBG, the reseed counter is used to update the value of *V* as well as to count the number of generation requests.

The following process or its equivalent **shall** be used as the generate algorithm for this DRBG (see step 8 of Section 9.4):

Input:

1. *working_state*: The current values for *V*, *C* and *reseed_counter* (see Section 10.1.2.2.1).
2. *requested_number_of_bits*: The number of pseudorandom bits to be returned to the generate function.
3. *additional_input*: The additional input string received from the consuming application. If *additional_input* will never be provided, then step 2 may be

omitted.

Output:

1. *status*: The status returned from the function. The *status* will indicate SUCCESS or indicate that a reseed is required before the requested pseudorandom bits can be generated. In the latter case, either nothing but the reseed indication **shall** be returned as output, or a *Null* string **shall** be returned as the *returned_bits* (see below).
2. *returned_bits*: The pseudorandom bits to be returned to the generate function.
3. *working_state*: The new values for *V*, *C* and *reseed_counter*.

Process:

1. If *reseed_counter* > *reseed_interval*, then return an indication that a reseed is required.
2. If (*additional_input* ≠ *Null*), then do
 - 2.1 $w = \text{Hash}(0x02 \parallel V \parallel \text{additional_input})$.
 - 2.2 $V = (V + w) \bmod 2^{\text{seedlen}}$.
3. *returned_bits* = **Hashgen** (*requested_number_of_bits*, *V*).
4. $H = \text{Hash}(0x03 \parallel V)$.
5. $V = (V + H + C + \text{reseed_counter}) \bmod 2^{\text{seedlen}}$.
6. *reseed_counter* = *reseed_counter* + 1.
7. Return SUCCESS, *returned_bits*, and the new values of *V*, *C* and *reseed_counter* for the new *working_state*.

Hashgen (...):

Input:

1. *requested_no_of_bits*: The number of bits to be returned.
2. *V*: The current value of *V*.

Output:

1. *returned_bits*: The generated bits to be returned to the generate function.

Process:

1. $m = \left\lceil \frac{\text{requested_no_of_bits}}{\text{outlen}} \right\rceil$.
2. $\text{data} = V$.
3. $W = \text{the Null string}$.

4. For $i = 1$ to m
 - 4.1 $w_i = \text{Hash}(data)$.
 - 4.2 $W = W \parallel w_i$.
 - 4.3 $data = (data + 1) \bmod 2^{seedlen}$.
5. $returned_bits = \text{Leftmost} (requested_no_of_bits)$ bits of W .
6. Return $returned_bits$.

10.1.3 HMAC_DRBG (...)

10.1.3.1 Discussion

HMAC_DRBG uses multiple occurrences of an Approved keyed hash function, which is based on an Approved hash function. The same hash function **shall** be used throughout. The hash function used **shall** meet or exceed the security requirements of the consuming application.

Figure 9 depicts the **HMAC_DRBG** in stages. **HMAC_DRBG** is specified using an internal function (**Update**). This function is called during the **HMAC_DRBG** instantiate, generate and reseed algorithms to adjust the internal state when new entropy or additional input is provided. The operations in the top portion of the figure are only performed if the additional input is not null. Figure 10 depicts the **Update** function.

10.1.3.2 Specifications

10.1.3.2.1 HMAC_DRBG Internal State

The internal state for **HMAC_DRBG** consists of:

1. The *working_state*:
 - a. The value *V* of *outlen* bits, which is updated each time another *outlen* bits of output are produced (where *outlen* is specified in Table 3 of Section 10.1.1).
 - b. The *Key* of *outlen* bits, which is updated at least once each time the DRBG generates pseudorandom bits.
 - c. A counter (*reseed_counter*) that indicates the number of requests for pseudorandom bits since instantiation or reseeding.

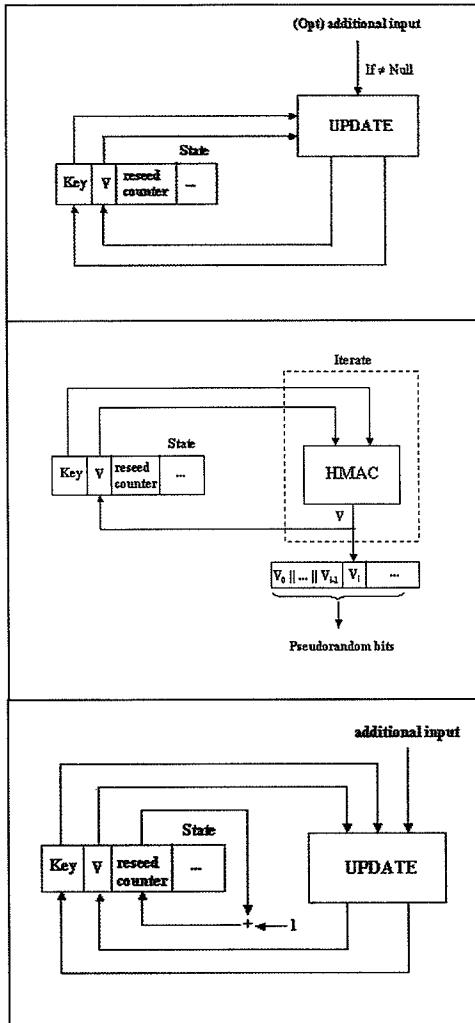


Figure 9: HMAC_DRBG

2. Administrative information:

- a. The *security_strength* of the DRBG instantiation.
- b. A *prediction_resistance_flag* that indicates whether or not a prediction resistance capability is required for the DRBG.

The values of V and Key are the critical values of the internal state upon which the security of this DRBG depends (i.e., V and Key are the “secret values” of the internal state).

10.1.3.2.2 The Update Function (Update)

The **Update** function updates the internal state of **HMAC_DRBG** using the *provided_data*. Let **HMAC** be the keyed hash function specified in FIPS 198 using the hash function selected for the DRBG from Table 3 in Section 10.1.1.

The following or an equivalent process **shall** be used as the **Update** function.

Input:

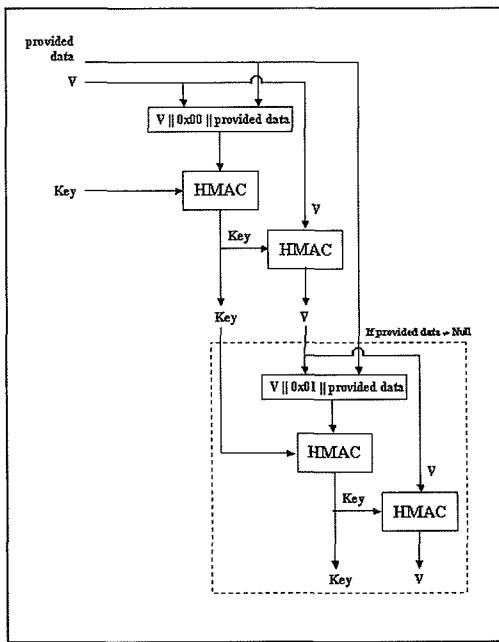
1. *provided_data*: The data to be used.
2. K : The current value of Key .
3. V : The current value of V .

Output:

1. K : The new value for Key .
2. V : The new value for V .

Process:

1. $K = \text{HMAC}(K, V \parallel 0x00 \parallel \text{provided_data})$.
2. $V = \text{HMAC}(K, V)$.
3. If (*provided_data* = Null), then return K and V .



4. $K = \mathbf{HMAC}(K, V \parallel 0x01 \parallel \text{provided_data})$.
 5. $V = \mathbf{HMAC}(K, V)$.
 6. Return K and V .

10.1.3.2.3 Instantiation of HMAC_DRBG

Notes for the instantiate function:

The instantiation of **HMAC_DRBG** requires a call to the instantiate function specified in Section 9.2; step 9 of that function calls the instantiate algorithm specified in this section. For this DRBG, no *DRBG_specific_input_parameters* are required for the instantiate function specified in Section 9.2 (i.e., step 5 **should** be omitted). The values of *highest_supported_security_strength* and *min_entropy_input_length* are provided in Table 3 of Section 10.1.1. The contents of the internal state are provided in Section 10.1.2.2.1.

The instantiate algorithm:

Let **Update** be the function specified in Section 10.1.3.2.2. The output block length (*outlen*) is provided in Table 3 of Section 10.1.1.

The following process or its equivalent **shall** be used as the instantiate algorithm for this DRBG (see step 8 of Section 9.2):

Input:

1. *entropy_input*: The string of bits obtained from the entropy input source.
 2. *nonce*: A string of bits as specified in Section 8.5.2.
 3. *personalization_string*: The personalization string received from the consuming application. If a *personalization_string* will never be used, then step 1 may be modified to remove the *personalization_string*.

Output:

1. *working_state*: The initial values for V , *Key* and *reseed_counter* (see Section 10.1.3.2.1).

Process:

- $seed_material = entropy_input \parallel nonce \parallel personalization_string.$
 - $Key = 0x00\ 00\dots 00.$ Comment: $outlen$ bits.
 - $V = 0x01\ 01\dots 01.$ Comment: $outlen$ bits.
Comment: Update Key and V .
 - $(Key, V) = \text{Update}(seed_material, Key, V).$
 - $reseed\ counter = 1.$

6. Return V , Key and $reseed_counter$ as the initial $working_state$.

10.1.3.2.4 Reseeding an HMAC_DRBG Instantiation

Notes for the reseed function:

The reseeding of an **HMAC_DRBG** instantiation requires a call to the reseed function specified in Section 9.3; step 5 of that function calls the reseed algorithm specified in this section. The values for $min_entropy_input_length$ are provided in Table 3 of Section 10.1.1.

The reseed algorithm:

Let **Update** be the function specified in Section 10.1.3.2.2. The following process or its equivalent **shall** be used as the reseed algorithm for this DRBG (see step 5 of Section 9.3):

Input:

1. $working_state$: The current values for V , Key and $reseed_counter$ (see Section 10.1.3.2.1).
2. $entropy_input$: The string of bits obtained from the entropy input source.
3. $additional_input$: The additional input string received from the consuming application. If $additional_input$ will never be used, then step 1 may be modified to remove the $additional_input$.

Output:

1. $working_state$: The new values for V , Key and $reseed_counter$.

Process:

1. $seed_material = entropy_input \parallel additional_input$.
2. $(Key, V) = \text{Update} (seed_material, Key, V)$.
3. $reseed_counter = 1$.
4. Return V , Key and $reseed_counter$ as the new $working_state$.

10.1.3.2.5 Generating Pseudorandom Bits Using HMAC_DRBG

Notes for the generate function:

The generation of pseudorandom bits using an **HMAC_DRBG** instantiation requires a call to the generate function specified in Section 9.4; step 8 of that function calls the generate algorithm specified in this section. The values for $max_number_of_bits_per_request$ and $ouflen$ are provided in Table 3 of Section 10.1.1.

The generate algorithm :

Let **HMAC** be the keyed hash function specified in FIPS 198 using the hash function selected for the DRBG. The value for $reseed_interval$ is defined in Table 3 of Section

10.1.1.

The following process or its equivalent **shall** be used as the generate algorithm for this DRBG (see step 8 of Section 9.4):

Input:

1. *working_state*: The current values for *V*, *Key* and *reseed_counter* (see Section 10.1.3.2.1).
2. *requested_number_of_bits*: The number of pseudorandom bits to be returned to the generate function.
3. *additional_input*: The additional input string received from the consuming application. If an implementation will never use *additional_input*, then step 2 may be omitted. If *additional_input* is not provided (regardless of whether or not it will ever be provided), then a *Null* string **shall** be used as the *additional_input* in step 5.

Output:

1. *status*: The status returned from the function. The *status* will indicate **SUCCESS** or indicate that a reseed is required before the requested pseudorandom bits can be generated. In the latter case, either nothing but the reseed indication **shall** be returned as output, or a *Null* string **shall** be returned as the *returned_bits* (see below).
2. *returned_bits*: The pseudorandom bits to be returned to the generate function.
3. *working_state*: The new values for *V*, *Key* and *reseed_counter*.

Process:

1. If *reseed_counter* > *reseed_interval*, then return an indication that a reseed is required.
2. If *additional_input* ≠ *Null*, then $(Key, V) = \text{Update}(\text{additional_input}, Key, V)$.
3. *temp* = *Null*.
4. While (*len* (*temp*) < *requested_number_of_bits*) do:
 - 4.1 $V = \text{HMAC}(Key, V)$.
 - 4.2 $\text{temp} = \text{temp} \parallel V$.
5. *returned_bits* = Leftmost *requested_number_of_bits* of *temp*.
6. $(Key, V) = \text{Update}(\text{additional_input}, Key, V)$.
7. *reseed_counter* = *reseed_counter* + 1.
8. Return **SUCCESS**, *returned_bits*, and the new values of *Key*, *V* and *reseed_counter* as the *working_state*.

10.2 DRBGs Based on Block Ciphers

10.2.1 Discussion

A block cipher DRBG is based on a block cipher algorithm. The block cipher DRBGs specified in this Standard have been designed to use any Approved block cipher algorithm and may be used by applications requiring various levels of security, providing that the appropriate block cipher algorithm and key length are used and sufficient entropy is obtained for the seed. The following are provided as DRBGs based on block cipher algorithms:

1. The **CTR_DRBG** specified in Section 10.2.2.
2. The **OFB_DRBG** specified in Section 10.2.3.

Table 4 specifies the values that shall be used for the function envelopes and DRBG algorithm for each Approved block cipher algorithm. The specifications in this Standard assume that a single appropriate block cipher algorithm and key size will be selected for a DRBG implementation; i.e., a DRBG implementation will not contain multiple block cipher algorithms or key sizes from which to choose during instantiation.

Table 4: Definitions for Block Cipher- Based DRBGs

	3 Key TDEA	AES-128	AES-192	AES-256
Supported security strengths	112	112, 128	112, 128, 192	112, 128, 192, 256
<i>highest_supported_security_strength</i>	112	128	192	256
Output block length (<i>outlen</i>)	64	128	128	128
Key length (<i>keylen</i>)	168	128	192	256
Required minimum entropy for instantiate and reseed	<i>security_strength</i>			
Seed length (<i>seedlen</i> = <i>outlen</i> + <i>keylen</i>)	232	256	320	384
A derivation function is used:				
Minimum entropy input length (<i>min_entropy_input_length</i>)	<i>security_strength</i>			
Maximum entropy input length (<i>max_entropy_input_length</i>)	$\leq 2^{35}$ bits			
Maximum personalization string length (<i>max_personalization_string_length</i>)	$\leq 2^{35}$ bits			

	3 Key TDEA	AES-128	AES-192	AES-256
Maximum additional_input length (max_additional_input_length)	$\leq 2^{35}$ bits			
A derivation function is not used (full entropy is available):				
Minimum entropy input length (min_entropy_input_length) (outlen + keylen)	<i>seedlen</i>			
Maximum entropy input length (max_entropy_input_length) (outlen + keylen)	<i>seedlen</i>			
Maximum personalization string length (max_personalization_string_length)	<i>seedlen</i>			
Maximum additional_input length (max_additional_input_length)	<i>seedlen</i>			
max_number_of_bits_per_request	$\leq 2^{13}$	$\leq 2^{19}$		
Number of requests between reseeds (reseed_interval)	$\leq 2^{32}$	$\leq 2^{48}$		

The block cipher DRBGs may be implemented to use the block cipher derivation function specified in Section 9.6.3. However, these DRBGs are specified to allow an implementation tradeoff with respect to the use of this derivation function. If a source for full entropy input is always available to provide entropy input when requested, the use of the derivation function is optional; otherwise, the derivation function shall be used. Table 4 provides lengths required for the *entropy_input*, *personalization_string* and *additional_input* for each case.

When full entropy is available, and a derivation function is not used by an implementation, the seed construction (seeSection 8.4.2) shall not use a nonce³.

When using TDEA as the selected block cipher algorithm, the keys shall be handled as 64-bit blocks containing 56 bits of key and 8 bits of parity as specified for the TDEA engine.

³ The specifications in this Standard do not accommodate the special treatment required for a nonce in this case.

10.2.2 CTR_DRBG

10.2.2.1 Discussion

CTR_DRBG uses an Approved block cipher algorithm in the counter mode as specified in [SP 800-38A]. The same block cipher algorithm and key length shall be used for all block cipher operations. The block cipher algorithm and key length shall meet or exceed the security requirements of the consuming application. The values to be used for the implementation of this DRBG are specified in Table 4 of Section 10.2.1.

CTR_DRBG is specified using an internal function (**Update**). Figure 11 depicts the **Update** function. This function is called by the instantiate, generate and reseed algorithms to adjust the internal state when new entropy or additional input is provided. Figure 12 depicts the **CTR_DRBG** in three stages. The operations in the top portion of the figure are only performed if the additional input is not null.

10.2.2.2 Specifications

10.2.2.2.1 CTR_DRBG Internal State

The internal state for **CTR_DRBG** consists of:

1. The *working_state*:
 - a. The value V of $outlen$ bits, which is updated each time another $outlen$ bits of output are produced (see Table 4 in Section 10.2.1).
 - b. The *Key* of $keylen$ bits, which is updated whenever a predetermined number of output blocks are generated.
 - c. A counter (*reseed_counter*) that indicates the number of requests for pseudorandom bits since instantiation or reseeding.
2. Administrative information:
 - a. The *security_strength* of the DRBG instantiation.
 - b. A *prediction_resistance_flag* that indicates whether or not a prediction resistance capability is required for the DRBG.

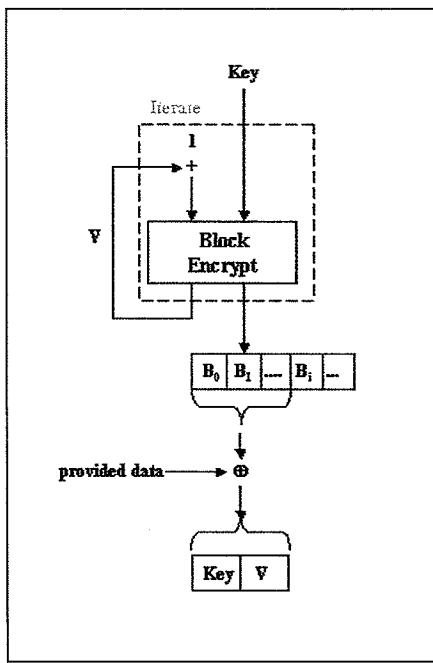


Figure 11: CTR_DRBG Update

The values of V and Key are the critical values of the internal state upon which the security of this DRBG depends (i.e., V and Key are the “secret values” of the internal state).

10.2.2.2.2 The Update Function (Update)

The **Update** function updates the internal state of the **CTR_DRBG** using the *provided_data*. The values for *outlen*, *keylen* and *seedlen* are provided in Table 4 of Section 10.2.1. The block cipher operation in step 2.2 uses the selected block cipher algorithm.

The following or an equivalent process shall be used as the **Update** function.

Input:

1. *provided_data*: The data to be used. This must be exactly *seedlen* bits in length; this length is guaranteed by the construction of the *provided_data* in the instantiate, reseed and generate functions.
2. *Key*: The current value of *Key*.
3. *V*: The current value of *V*.

Output:

1. *K*: The new value for *Key*.
2. *V*: The new value for *V*.

Process:

1. *temp* = Null.
2. While (*len* (*temp*) < *seedlen*) do
 - 2.1 $V = (V + 1) \bmod 2^{outlen}$
 - 2.2 *output_block* = **Block_Encrypt** (*Key*, *V*).
 - 2.3 *temp* = *temp* || *output_block*.

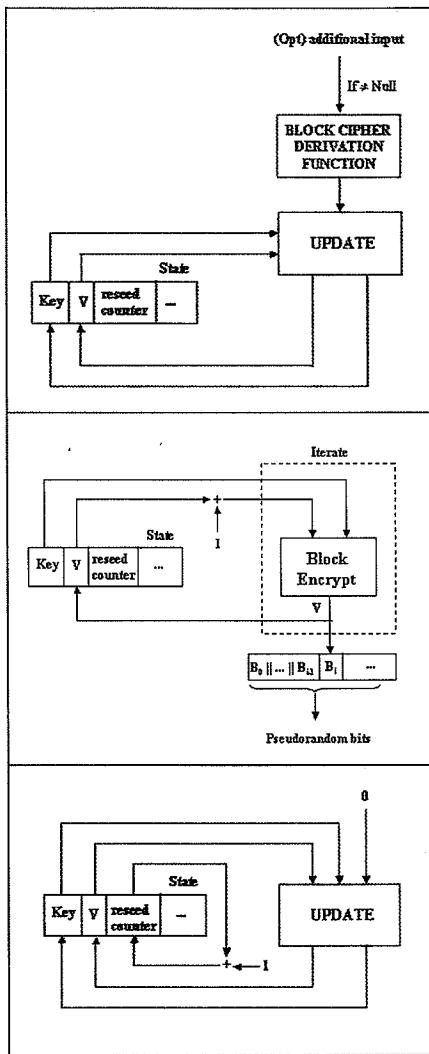


Figure 12: CTR_DRBG

3. $\text{temp} = \text{Leftmost } \text{seedlen} \text{ bits of } \text{temp}.$
4. $\text{temp} = \text{temp} \oplus \text{provided_data}.$
5. $\text{Key} = \text{Leftmost } \text{keylen} \text{ bits of } \text{temp}.$
6. $V = \text{Rightmost } \text{outlen} \text{ bits of } \text{temp}.$
7. Return the new values of Key and V .

10.2.2.2.3 Instantiation of CTR_DRBG

Notes for the instantiate function:

The instantiation of **CTR_DRBG** requires a call to the instantiate function specified in Section 9.2; step 9 of that function calls the instantiate algorithm specified in this section. For this DRBG, no *DRBG_specific_input_parameters* are required for the instantiate function specified in Section 9.2 (i.e., step 5 **should** be omitted). The values of *highest_supported_security_strength* and *min_entropy_input_length* are provided in Table 4 of Section 10.2.1. The contents of the internal state are provided in Section 10.2.2.2.1.

The instantiate algorithm:

Let **Update** be the function specified in Section 10.2.2.2, and let **Block_Cipher_df** be the derivation function specified in Section 9.6.3 using the chosen block cipher algorithm and key size. The output block length (*outlen*), key length (*keylen*), seed length (*seedlen*) and *security_strengths* for the block cipher algorithms are provided in Table 4 of Section 10.2.1.

The following process or its equivalent **shall** be used as the instantiate algorithm for this DRBG:

Input:

1. *entropy_input*: The string of bits obtained from the entropy input source.
2. *nonce*: A string of bits as specified in Section 8.5.2; this string **shall not** be present when a derivation function is not used.
3. *personalization_string*: The personalization string received from the consuming application.

Output:

1. *working_state*: The initial values for V , Key and *reseed_counter* (see Section 10.2.2.2.1).

Process:

1. If the block cipher derivation function is available, then
 - 1.1 $\text{seed_material} = \text{entropy_input} \parallel \text{nonce} \parallel \text{personalization_string}.$

- 1.2 $seed_material = \text{Block_Cipher_df}(seed_material, seedlen)$.
Else Comment: The block cipher derivation function is not used and full entropy is known to be available.
- 1.3 $temp = \text{len}(\text{personalization_string})$.
- 1.4 If $temp > seedlen$, then return an **ERROR**.
- 1.5 If $(temp < seedlen)$, then $\text{personalization_string} = \text{personalization_string} \parallel 0^{seedlen - temp}$.
- 1.6 $seed_material = \text{entropy_input} \oplus \text{personalization_string}$.
2. $Key = 0^{keylen}$. Comment: $keylen$ bits of zeros.
3. $V = 0^{outlen}$. Comment: $outlen$ bits of zeros.
4. $(Key, V) = \text{Update}(seed_material, Key, V)$.
5. $reseed_counter = 1$.
6. Return V , Key and $reseed_counter$ as the *working state*.

Implementation notes:

1. Step 1 should consist of either steps 1.1 and 1.2, or steps 1.3 – 1.6. The decision for the substeps to be used depends on whether the implementation has full entropy and is using the derivation function.
 2. If a *personalization_string* will never be provided from the instantiate function and a derivation function will be used, then step 1.1 becomes:

seed_material = **Block_Cipher_df** (*entropy_input*, *seedlen*).

3. If a *personalization_string* will never be provided from the `instantiate` function, a full entropy source will be available and a derivation function will not be used, then step 1 becomes

seed material = entropy input.

That is, steps 1.3 – 1.6 collapse into the above step.

10.2.2.4 Reseeding a CTR_DRBG Instantiation

Notes for the reseed function:

The reseeding of a **CTR_DRBG** instantiation requires a call to the reseed function specified in Section 9.3; step 5 of that function calls the reseed algorithm specified in this section. The values for *min_entropy_input_length* are provided in Table 4 of Section 10.2.1.

The reseed algorithm:

Let **Update** be the function specified in Section 10.2.2.2.2, and let **Block_Cipher_df** be the derivation function specified in Section 9.6.3 using the chosen block cipher algorithm and key size. The seed length (*seedlen*) is provided in Table 4 of Section 10.2.1.

The following process or its equivalent **shall** be used as the reseed algorithm for this DRBG (see step 5 of Section 9.3):

Input:

1. *working_state*: The current values for *V*, *Key* and *reseed_counter* (see Section 10.2.2.2.1).
2. *entropy_input*: The string of bits obtained from the entropy input source.
3. *additional_input*: The additional input string received from the consuming application.

Output:

1. *working_state*: The new values for *V*, *Key* and *reseed_counter*.

Process:

1. If the block cipher derivation function is available, then
 - 1.1 $seed_material = entropy_input \parallel additional_input$.
 - 1.2 $seed_material = \text{Block_Cipher_df}(seed_material, seedlen)$.
 Else

Comment: The block cipher derivation function is not used because full entropy is known to be available.

 - 1.3 $temp = \text{len}(additional_input)$.
 - 1.4 If $temp > seedlen$, then return an **ERROR**.
 - 1.5 If ($temp < seedlen$), then $additional_input = additional_input \parallel 0^{seedlen - temp}$.
 - 1.6 $seed_material = entropy_input \oplus additional_input$.
2. $(Key, V) = \text{Update}(seed_material, Key, V)$.
3. $reseed_counter = 1$.
4. Return *V*, *Key* and *reseed_counter* as the *working_state*.

Implementation notes:

1. Step 1 should consist of either steps 1.1 and 1.2, or steps 1.3 – 1.6. The decision for the substeps to be used depends on whether the implementation has full

entropy and is using the derivation function.

2. If *additional_input* will never be provided from the reseed function and a derivation function will be used, then step 1.1 becomes:

$$\text{seed_material} = \text{Block_Cipher_df}(\text{entropy_input}, \text{seedlen}).$$
3. If *additional_input* will never be provided from the reseed function, a full entropy source will be available and a derivation function will not be used, then step 1 becomes

$$\text{seed_material} = \text{entropy_input}.$$

That is, steps 1.3 – 1.6 collapse into the above step.

10.2.2.2.5 Generating Pseudorandom Bits Using CTR_DRBG

Notes for the generate function:

The generation of pseudorandom bits using a CTR_DRBG instantiation requires a call to the generate function specified in Section 9.4, step 8 of that function calls the generate algorithm specified in this section. The values for *max_number_of_bits_per_request* and *outlen* are provided in Table 4 of Section 10.2.1. If the derivation function is not used, then the maximum allowed length of *additional_input* = *seedlen*.

The following process or its equivalent **shall** be used as the generate algorithm for this DRBG (see step 8 of Section 9.4):

Let **Block_Cipher_df** be the derivation function specified in Section 9.6.3, and let **Update** be the function specified in Section 10.2.2.2 using the chosen block cipher algorithm and key size. The seed length (*seedlen*) and the value of *reseed_interval* are provided in Table 4 of Section 10.2.1. Step 4.2 below uses the selected block cipher algorithm. If a derivation function is not used for a DRBG implementation, then step 2.2 **shall** be omitted.

The following process or its equivalent **shall** be used as generate algorithm for this DRBG (see step 8 of Section 9.4):

Input:

1. *working_state*: The current values for *V*, *Key* and *reseed_counter* (see Section 10.2.2.2.1).
2. *requested_number_of_bits*: The number of pseudorandom bits to be returned to the generate function.
3. *additional_input*: The additional input string received from the consuming application. If *additional_input* will never be provided, then step 2 may be omitted.

Output:

1. *status*: The status returned from the function. The *status* will indicate **SUCCESS**, indicate that a reseed is required before the requested pseudorandom bits can be generated, or indicate that the *additional_input* is too long. If **SUCCESS** is not returned, either nothing but the reseed indication shall be returned as output, or a *Null* string shall be returned as the *returned_bits* (see below).
2. *returned_bits*: The pseudorandom bits returned to the generate function.
3. *working_state*: The new values for *V*, *Key* and *reseed_counter*.

Process:

1. If *reseed_counter* > *reseed_interval*, then return an indication that a reseed is required.
2. If (*additional_input* ≠ *Null*), then

Comment: If the length of the *additional_input* is > *seedlen*, derive *seedlen* bits.

 - 2.1 *temp* = **len** (*additional_input*).

Comment: If a block cipher derivation function is used:
 - 2.2 If (*temp* > *seedlen*), then *additional_input* = **Block_Cipher_df** (*additional_input*, *seedlen*).

Comment: If the length of the *additional_input* is < *seedlen*, pad with zeros to *seedlen* bits.
 - 2.3 If (*temp* < *seedlen*), then *additional_input* = *additional_input* || 0^{*seedlen* - *temp*}.
 - 2.4 (*Key*, *V*) = **Update** (*additional_input*, *Key*, *V*).
3. *temp* = *Null*.
4. While (**len** (*temp*) < *requested_number_of_bits*) do:
 - 4.1 *V* = (*V* + 1) mod 2^{*outlen*}.
 - 4.2 *output_block* = **Block_Encrypt** (*Key*, *V*).
 - 4.3 *temp* = *temp* || *output_block*.
5. *returned_bits* = Leftmost *requested_number_of_bits* of *temp*.

Comment: Update for backtracking resistance.
6. *zeros* = 0^{*seedlen*}.

Comment: Produce a string of

seedlen zeros.

7. $(Key, V) = \text{Update}(\text{zeros}, Key, V)$.
8. $\text{reseed_counter} = \text{reseed_counter} + 1$.
9. Return **SUCCESS** and *returned_bits*; also return *Key*, *V* and *reseed_counter* as the new *working_state*.

10.2.3 OFB_DRBG

10.2.3.1 Discussion

OFB_DRBG uses an Approved block cipher algorithm in the output feedback mode as specified in [SP 800-38A]. The same block cipher algorithm and key length **shall** be used for all block cipher operations. The block cipher algorithm and key length **shall** meet or exceed the security requirements of the consuming application. The values to be used for the implementation of this DRBG are specified in Table 4 in Section 10.2.1.

OFB_DRBG is specified using an internal function (**Update**). Figure 13 depicts the **OFB_DRBG** in three stages. The operations in the top portion of the figure are only performed if non-null additional input is provided. Figure 14 depicts the **Update** function. This function is called by the instantiate, generate and reseed algorithms to adjust the internal state when new entropy or additional input is provided. Note that **OFB_DRBG** is basically the same as **CTR_DRBG**, except that the block cipher mode is OFB rather than CTR.

10.2.3.2 Specifications

10.2.3.2.1 OFB_DRBG Internal State

The internal state for **OFB_DRBG** consists of:

1. The working_state:

 - a. The value V , which is updated each time another *outlen* bits of output are produced.
 - b. The *Key*, which is updated whenever a predetermined number of output blocks are generated.
 - c. A counter (*reseed_counter*) that

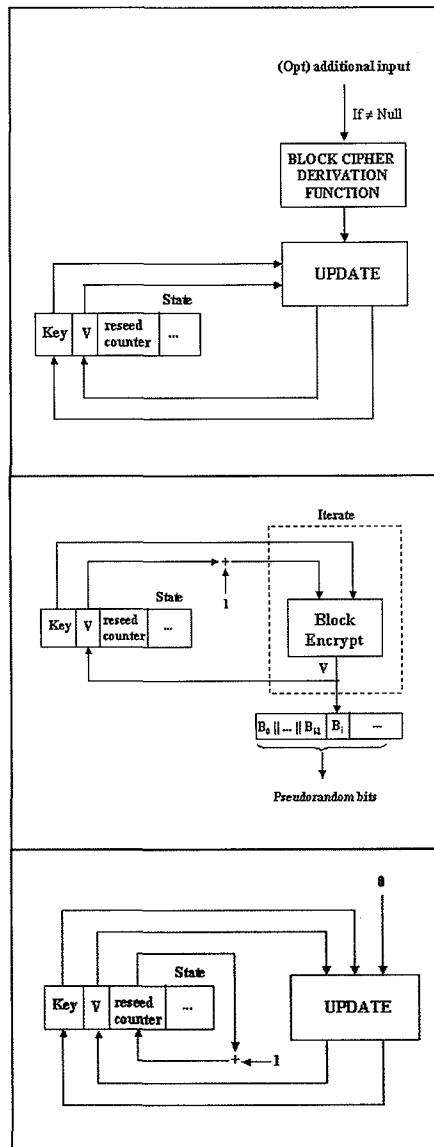


Figure 13: OFB_DRBG

indicates the number of requests for pseudorandom bits since instantiation or reseeding.

2. Administrative information:
 - a. The security *strength* of the DRBG instantiation.
 - b. A *prediction_resistance_flag* that indicates whether or not a prediction resistance capability is required for the DRBG.

The values of *V* and *Key* are the critical values of the internal state upon which the security of this DRBG depends (i.e., *V* and *Key* are the “secret values” of the internal state).

10.2.3.2.2 The Update Function(Update)

The **Update** function updates the internal state of the **OFB_DRBG** using the *provided_data*. The values for *outlen*, *keylen* and *seedlen* are provided in Table 4 of Section 10.2.1. The block cipher operation in step 2.1 uses the selected block cipher algorithm and key size.

The following or an equivalent process **shall** be used as the **Update** function.

Input:

1. *provided_data*: The data to be used.
2. *Key*: The current value of *Key*.
3. *V*: The current value of *V*.

Output:

1. *K*: The new value for *Key*.
2. *V*: The new value for *V*.

Process:

1. *temp* = *Null*.
2. While (*len* (*temp*) < *seedlen*) do
 - 2.1 *V* = **Block_Encrypt** (*Key*, *V*).
 - 2.2 *temp* = *temp* || *V*.

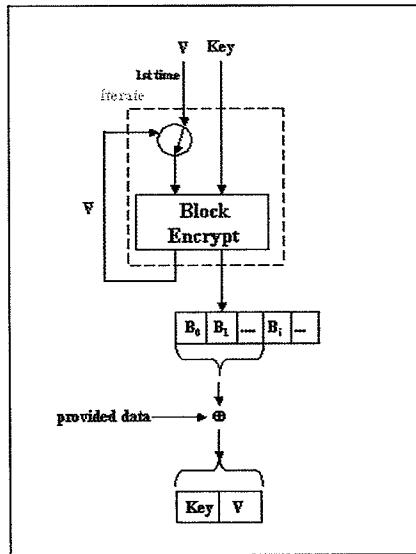


Figure 14: OFB_DRBG Update

3. temp = Leftmost seedlen bits of temp .
4. $\text{temp} = \text{temp} \oplus \text{provided_data}$.
5. Key = Leftmost keylen bits of temp .
6. V = Rightmost outlen bits of temp .
7. Return the new values of Key and V .

10.2.3.2.3 Instantiation of OFB_DRBG (...)

This process is the same as the instantiation process for **CTR_DRBG** in Section 10.2.2.2.3, except that the **Update** function to be used is specified in Section 10.2.3.2.2.

10.2.3.2.4 Reseeding an OFB_DRBG Instantiation

This process is the same as the reseeding process for **CTR_DRBG** in Section 10.2.2.2.4, except that the **Update** function to be used is specified in Section 10.2.3.2.2

10.2.3.2.5 Generating Pseudorandom Bits Using OFB_DRBG

This process is the same as the generation process for **CTR_DRBG** in Section 10.2.2.2.5, except that the **Update** function to be used is specified in Section 10.2.3.2.2 and step 4 **shall** be as follows:

4. While (**len** (temp) < $\text{requested_number_of_bit}$) do:
 - 4.1 $V = \text{Block_Encrypt} (\text{Key}, V)$.
 - 4.2 $\text{temp} = \text{temp} \parallel V$.

10.3 Deterministic RBGs Based on Number Theoretic Problems

10.3.1 Discussion

A DRBG can be designed to take advantage of number theoretic problems (e.g., the discrete logarithm problem). If done correctly, such a generator's properties of randomness and/or unpredictability will be assured by the difficulty of finding a solution to that problem. Section 10.3.2 specifies a DRBG based on the elliptic curve discrete logarithm problem; Section 10.3.3 specifies a DRBG based on a problem related to the RSA problem of finding roots modulo a composite integer.

10.3.2 Dual Elliptic Curve Deterministic DRBG (Dual_EC_DRBG)

10.3.2.1 Discussion

Dual_EC_DRBG is based on the following hard problem, sometimes known as the “elliptic curve discrete logarithm problem” (ECDLP): given points P and Q on an elliptic curve of order n , find a such that $Q = aP$.

Dual_EC_DRBG uses a seed that is m bits in length (i.e., $seedlen = m$) to initiate the generation of $outlen$ -bit pseudorandom strings by performing scalar multiplications on two points in an elliptic curve group, where the curve is defined over a field approximately 2^m in size. For all the NIST curves given in this Standard, $m \geq 163$. Figure 15 depicts the **Dual_EC_DRBG**.

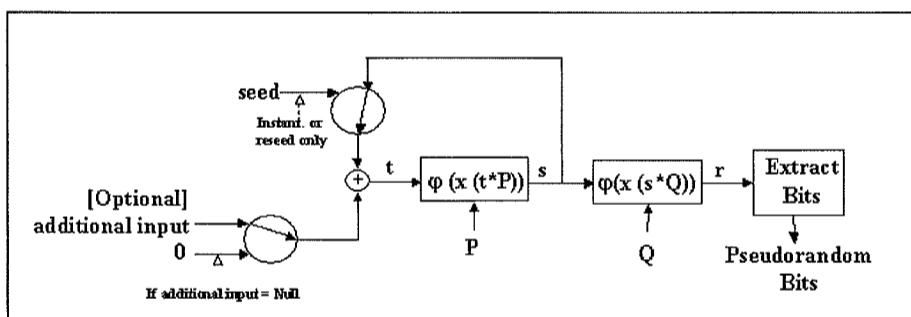


Figure 15: Dual_EC_DRBG

The instantiation of this DRBG requires the selection of an appropriate elliptic curve and curve points specified in Annex A.1 for the desired security strength. The *seed* used to determine the initial value (*s*) of the DRBG shall have entropy that is at least *security_strength* + 64 bits. Further requirements for the *seed* are provided in Section 8.4.

Backtracking resistance is inherent in the algorithm, even if the internal state is compromised. As shown in Figure 16, **Dual_EC_DRBG** generates a *seedlen*-bit number

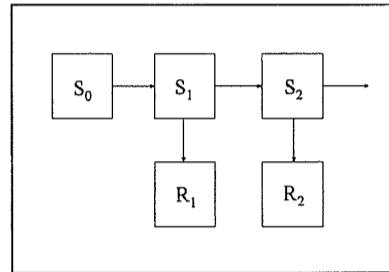
for each step $i = 1, 2, 3, \dots$, as follows:

$$\begin{aligned} S_i &= \varphi(x(S_{i-1} * P)) \\ R_i &= \varphi(x(S_i * Q)). \end{aligned}$$

Each arrow in the figure represents an Elliptic Curve scalar multiplication operation, followed by the extraction of the x coordinate for the resulting point and for the random output R_i , and by truncation to produce the output. Following a line in the direction of the arrow is the normal operation; inverting the direction implies the ability to solve the ECDLP for that specific curve. An adversary's ability to invert an arrow in the figure implies that the adversary has solved the ECDLP for that specific elliptic curve. Backtracking resistance is built into the design, as knowledge of S_1 does not allow an adversary to determine S_0 (and so forth) unless the adversary is able to solve the ECDLP for that specific curve. In addition, knowledge of R_1 does not allow an adversary to determine S_1 (and so forth) unless the adversary is able to solve the ECDLP for that specific curve.

Table 5 specifies the values that **shall** be used for the envelope and algorithm for each curve. Complete specifications for each curve are provided in Annex A.1. Note that all curves except the first three can be instantiated at a security strength lower than its highest possible security strength. For example, the highest security strength that can be supported by curve P-384 is 192 bits; however, this curve can alternatively be instantiated to support only the 112 or 128-bit security strengths).

Table 5: Definitions for the Dual_EC_DRBG



**Figure 16: Dual_EC_DRBG (...)
Backtracking Resistance**

	P-224	B-233	K-233	P-256	B-283	K-283
Supported security strengths	112	112	112	112, 128	112, 128	112, 128
highest_supported_security_strength	112	112	112	128	128	128
Output block length (outlen = largest multiple of 8 smaller than seedlen - (13 + log₂(the cofactor)))	208	216	216	240	264	264
Required minimum entropy for instantiate and reseed	security_strength					
Minimum entropy input length (min_entropy_input_length = 8 × ⌈seedlen/8⌉)	224	240	240	256	288	288

Comment [ebb4]: Page: 80
Why can't this be min_entropy ?

	P-224	B-233	K-233	P-256	B-283	K-283
Maximum entropy input length (max_entropy_input_length)	$\leq 2^{13}$ bits					
Maximum personalization string length (max_personalization_string_length)	$\leq 2^{13}$ bits					
Maximum additional_input length (max_additional_input_length)	$\leq 2^{13}$ bits					
Seed length (seedlen = m)	224	233	233	256	283	283
Appropriate hash functions	SHA-1, SHA-224, SHA-256, SHA-384, SHA-512					
max_number_of_bits_per_request	$outlen \times reseed_interval$					
Number of blocks between reseeding (reseed_interval)	$\leq 10,000$ blocks					

	P-384	B-409	K-409	P-521	B-571	K-571
Supported security strengths	112, 128, 192					
highest_supported_security_strength	192					
Output block length (outlen = smallest multiple of 8 larger than seedlen - (13 + log₂(the cofactor)))	368	392	392	504	552	552
Required minimum entropy for instantiate and reseed	security_stength					
Minimum entropy input length (min_entropy_input_length = 8 × ⌈ seedlen/8 ⌉)	384	416	416	528	576	576
Maximum entropy input length (max_entropy_input_length)	$\leq 2^{13}$ bits					
Maximum personalization string length (max_personalization_string_length)	$\leq 2^{13}$ bits					
Maximum additional_input length (max_additional_input_length)	$\leq 2^{13}$ bits					
Seed length (seedlen = m)	384	409	409	521	571	571
Appropriate hash functions	SHA-224, SHA-256, SHA-384, SHA-512					

	P-384	B-409	K-409	P-521	B-571	K-571
<i>max_number_of_bits_per_request</i>	<i>outlen × reseed_interval</i>					
Number of blocks between reseeding (<i>reseed_interval</i>)	$\leq 10,000$ blocks					

Validation and Operational testing are discussed in Section 11. Detected errors **shall** result in a transition to the error state.

10.3.2.2 Specifications

10.3.2.2.1 Dual_EC_DRBG Internal State and Other Specification Details

The internal state for **Dual_EC_DRBG** consists of:

1. The *working_state*:
 - a. A value (*s*) that determines the current position on the curve.
 - b. The elliptic curve domain parameters (*curve_type*, *seedlen*, *p*, *a*, *b*, *n*), where *curve_type* indicates a prime field F_p , or a pseudorandom or Koblitz curve over the binary field F_2^m ; *seedlen* is the length of the seed ; *a* and *b* are two field elements that define the equation of the curve, and *n* is the order of the point *G*. If only one curve will be used by an implementation, these parameters need not be present in the *working_state*. If only one type of curve is implemented, the *curve_type* parameter may be omitted.
 - c. Two points *P* and *Q* on the curve; the generating point *G* specified in FIPS 186-3 for the chosen curve will be used as *P*. If only one curve will be used by an implementation, these points need not be present in the *working_state*.
 - d. A counter (*block_counter*) that indicates the number of blocks of random produced by the **Dual_EC_DRBG** since the initial seeding or the previous reseeding.
2. Administrative information:
 - a. The *security_strength* provided by the instance of the DRBG,
 - b. A *prediction_resistance_flag* that indicates whether prediction resistance is required by the DRBG, and

The value of *s* is the critical value of the internal state upon which the security of this DRBG depends (i.e., *s* is the “secret value” of the internal state).

10.3.2.2.2 Instantiation of Dual_EC_DRBG

Notes for the instantiate function:

The instantiation of **Dual_EC_DRBG** requires a call to the instantiate function

specified in Section 9.2; step 9 of that function calls the instantiate algorithm in this section. For this DRBG, a DRBG-specific input parameter of *requested_curve_type* is optional (see the definition for *curve_type* in Section 10.3.2.2.1). If only one type of curve is available, then this parameter may be omitted. If multiple types are available, then a *Prime_field_curve* will be selected if the parameter is omitted; if a *Prime_field_curve* is not available, then a *Random_binary_curve* will be selected.

In step 5 of the instantiate function, the following step **shall** be performed to select an appropriate curve if multiple curves are available.

5. Using *requested_curve_type* (if provided), the *security_strength* and Table 5 in Section 10.3.2.1, select the smallest available curve that has a security strength $\geq \text{security_strength}$.
 - 5.1 If *requested_curve_type* is indicated, then select a curve of that type. If no suitable curve of that type is available for the *requested_security_strength*, then return an **ERROR**.
 - 5.2 If a curve type is not requested, then select an appropriate *Prime_field_curve* if a suitable curve is available. If no suitable *Prime_field_curve* is available, then select a *Random_binary_curve* if a suitable curve is available. If no suitable *Random_binary_curve* is available, then select a *Koblitz_curve*. If no suitable *Koblitz_curve* is available, then return an **ERROR**.

The values for *curve_type*, *seedlen*, *p*, *a*, *b*, *n*, *P*, *Q* are determined by that curve.

The values for *highest_supported_security_strength* and *min_entropy_input_length* are determined by the selected curve (see Table 5 in Section 10.3.2.1).

The instantiate algorithm :

Let **Hash_df** be the hash derivation function specified in Section 9.6.2 using an appropriate hash function from Table 5 in Section 10.3.2.1. Let *seedlen* be the appropriate value from Table 5.

The following process or its equivalent **shall** be used as the instantiate algorithm for this DRBG (see step 9 of Section 9.2):

Input:

1. *entropy_input*: The string of bits obtained from the entropy input source.
2. *nonce*: A string of bits as specified in Section 8.5.2.
3. *personalization_string*: The personalization string received from the consuming application.

Output:

1. *s*: The initial secret value for the *working_state*.

2. *block_counter*: The initialized block counter for reseeding.

Process:

1. *seed_material* = *entropy_input* || *nonce* || *personalization_string*.
Comment: Use a hash function to ensure that the entropy is distributed throughout the bits, and *s* is *m* (i.e., *seedlen*) bits in length.
2. *s* = **Hash_df** (*seed_material*, *seedlen*).
Comment: Save all state information.
3. *block_counter* = 0.
4. Return *s* and *block_counter* for the *working_state*.

Implementation notes:

If an implementation never uses a *personalization_string*, then steps 1 and 2 may be combined as follows :

s = **Hash_df** (*entropy_input*, *seedlen*).

10.3.2.2.3 Reseeding of a Dual_EC_DRBG Instantiation

Notes for the reseed function:

The reseed of **Dual_EC_DRBG** requires a call to the reseed function specified in Section 9.3; step 5 of that function calls the reseed algorithm in this section. The values for *min_entropy_input_length* are provided in Table 5 of Section 10.3.2.1.

The reseed algorithm :

Let **Hash_df** be the hash derivation function specified in Section 9.6.2 using an appropriate hash function from Table 5 in Section 10.3.2.1.

The following process or its equivalent **shall** be used to reseed the **Dual_EC_DRBG** process after it has been instantiated (see step 5 in Section 9.3):

Input:

1. *s*: The current value of the secret parameter in the *working_state*.
2. *entropy_input*: The string of bits obtained from the entropy input source.
3. *additional_input*: The additional input string received from the consuming application.

Output:

1. *s*: The new value of the secret parameter in the *working_state*.
2. *block_counter*: The re-initialized block counter for reseeding.

Process:

Comment: **pad8** returns a copy of *s* padded on the right with binary 0's, if necessary, to a multiple of 8.

1. *seed_material* = **pad8** (*s*) || *entropy_input* || *additional_input_string*.
2. *s* = **Hash_df** (*seed_material*, *seedlen*).
3. *block_counter* = 0.
4. Return *s* and *block_counter* for the new *working_state*.

Implementation notes:

If an implementation never allows *additional_input*, then step 1 may be modified as follows :

seed_material = **pad8** (*s*) || *entropy_input*.

10.3.2.2.4 Generating Pseudorandom Bits Using Dual_EC_DRBG

Notes for the generate function:

The generation of pseudorandom bits using a **Dual_EC_DRBG** instantiation requires a call to the generate function specified in Section 9.4; step 8 of that function calls the generate algorithm specified in this section. The values for *max_number_of_bits_per_request* and *outlen* are provided in Table 4 of Section 10.2.1.

The generate algorithm:

Let **Hash_df** be the hash derivation function specified in Section 9.6.2 using an appropriate hash function from Table 5 in Section 10.3.2.1. The value of *reseed_interval* is also provided in Table 5.

The following are used by the generate algorithm:

- a. **pad8** (*bitstring*) returns a copy of the *bitstring* padded on the right with binary 0's, if necessary, to a multiple of 8.
- b. **Truncate** (*bitstring*, *in_len*, *out_len*) inputs a *bitstring* of *in_len* bits, returning a string consisting of the leftmost *out_len* bits of *bitstring*. If *in_len* < *out_len*, the *bitstring* is padded on the right with (*out_len* - *in_len*) zeroes, and the result is returned.
- c. *x(A)* is the *x*-coordinate of the point *A* on the curve.
- d. $\varphi(x)$ maps field elements to non-negative integers, taking the bit vector representation of a field element and interpreting it as the binary expansion of an integer. Section 10.3.2.2.4 has the details of this mapping.

The precise definition of $\varphi(x)$ used in steps 6 and 7 below depends on the field representation of the curve points. In keeping with the convention of FIPS 186-

2, the following elements will be associated with each other (note that $m = seedlen$):

$B: |c_{m-1}|c_{m-2}| \dots |c_1|c_0|$, a bitstring, with c_{m-1} being leftmost

$Z: c_{m-1}2^{m-1} + \dots + c_22^2 + c_12^1 + c_0 \in Z$;

$Fa: c_{m-1}2^{m-1} + \dots + c_22^2 + c_12^1 + c_0 \bmod p \in GF(p)$;

$Fb: c_{m-1}t^{m-1} \oplus \dots \oplus c_2t^2 \oplus c_1t \oplus c_0 \in GF(2^m)$, when a polynomial basis is used;

$Fc: c_{m-1}\beta \oplus c_{m-2}\beta^2 \oplus c_{m-3}\beta^{2^2} \oplus \dots \oplus c_0\beta^{2^{m-1}} \in GF(2^m)$, when a normal basis is used.

Thus, any field element x of the form Fa , Fb or Fc will be converted to the integer Z or bitstring B , and vice versa, as appropriate.

- e. * is the symbol representing scalar multiplication of a point on the curve.

The following process or its equivalent **shall** be used to generate pseudorandom bits (see step 8 in Section 9.4):

Input:

1. *working_state*: The current values for s , *curve_type*, *seedlen*, p , a , b , n , P , Q and *reseed_counter* (see Section 10.1.3.2.1).
2. *requested_number_of_bits*: The number of pseudorandom bits to be returned to the generate function.
3. *additional_input*: The additional input string received from the consuming application.

Output:

1. *status*: The status returned from the function. The *status* will indicate **SUCCESS** or indicate that a reseed is required before the requested pseudorandom bits can be generated. In the latter case, either nothing but the reseed indication **shall** be returned as output, or a *Null* string **shall** be returned as the *returned_bits* (see below).
2. *returned_bits*: The pseudorandom bits to be returned to the generate function.
3. *s*: The new value for the secret parameter in the *working_state*.
4. *block_counter*: The updated block counter for reseeding.

Process:

Comment: Check whether a reseed is required.

1. If $\left(\text{block_counter} + \left\lceil \frac{\text{requested_number_of_bits}}{\text{outlen}} \right\rceil \right) > \text{reseed_interval}$, then return an indication that a reseed is required.
Comment: If *additional_input* is Null, set to *seedlen* zeroes; otherwise, **Hash_df** to *seedlen* bits.
2. If (*additional_input_string* = Null), then *additional_input* = 0
Else *additional_input* = **Hash_df** (**pad8** (*additional_input_string*), *seedlen*).
Comment: Produce *requested_no_of_bits*, *outlen* bits at a time:
3. *temp* = the Null string.
4. *i* = 0.
5. *t* = *s* \oplus *additional_input*.
6. *s* = $\phi(x(t * P))$.
Comment: *t* is to be interpreted as a *seedlen*-bit unsigned integer. To be precise, when *curve_type* = *Prime_field_curve*, *t* should be reduced mod *n*; the operation * will effect this. *s* is a *seedlen*-bit number.
7. *r* = $\phi(x(s * Q))$.
Comment: *r* is a *seedlen*-bit number.
8. *temp* = *temp* || (rightmost *outlen* bits of *r*).
9. *additional_input*=0
Comment: *seedlen* zeroes; *additional_input_string* is added only on the first iteration.
10. *block_counter* = *block_counter* + 1.
11. *i* = *i* + 1.
12. If (**len** (*temp*) < *requested_number_of_bits*), then go to step 5.
13. *returned_bits* = **Truncate** (*temp*, *i* \times *outlen*, *requested_number_of_bits*).
14. Return **SUCCESS**, *returned_bits*, and *s* and *block_counter* for the *working_state*.

10.3.3 Micali-Schnorr Deterministic RBG (MS_DRBG)

10.3.3.1 Discussion

The **MS_DRBG** generalizes the RSA generator, which is defined as follows: Let $\gcd(x, y)$ denote the greatest common divisor of the integers x and y , and $\phi(n)$ represent the Euler phi function⁴. Select n , the product of two distinct large primes, and e , a positive integer such that $\gcd(e, \phi(n)) = 1$. Define $f(y) = y^e \bmod n$. Starting with a seed y_0 , form the sequence $y_{i+1} = f(y_i)$, and output the string consisting of the $\lg \lg(n)$ least significant bits of each y_i . These bits are known to be as secure as the RSA function f , and are commonly referred to as the *hard* bits.

The Micali-Schnorr generator **MS_DRBG** uses the same e and n as the RSA generator, but produces many more random bits per iteration and eliminates the overlap between the state sequence and the output bits. Each $y_i \in [0, n)$ is viewed as the concatenation $s_i \parallel z_i$ of an r -bit number s_i and a $k = \lg(n)-r$ bit number z_i . The s_i are used to propagate the integer sequence $y_{i+1} = s_i^e \bmod n$; the z_i are output as random bits. r must be at least $2 * \min\{\text{security_strength}, \lg(n)/e\}$, where *security_strength* is the desired security strength of the generator, and $e \geq 65,537$. (See Section 10.3.3.2.2). A random r -bit *seed* s_0 is used to initialize the process.

Figure 17 depicts the **MS_DRBG**. Under the proper assumption, the **MS_DRBG** is an example of a cryptographically secure generator, i.e., one that passes all polynomial-time statistical tests. The assumption is that sequences of the form $s^e \bmod n$ are statistically the same as sequences of integers in Z_n . This assumption is stronger than requiring the intractability of the RSA problem. See [1] for a discussion of these concepts and references to further details.

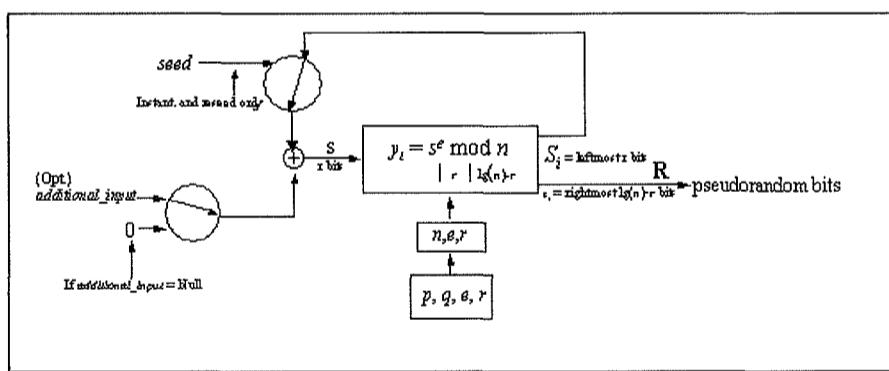


Figure 17: MS_DRBG

⁴ The Euler phi function : $\phi(n) =$ the number of positive integers $< n$ that are relatively prime to n . For an RSA modulus $n = pq$, $\phi(n) = (p-1)(q-1)$.

For **MS_DRBG**, the s values are assumed to be r -bit integers, and “statistically the same” means indistinguishable by any polynomial-time algorithm. Accepting the stronger assumption allows k to be a significant percentage of $\lg(n)$. Note that in the specifications, r has been redefined as *seedlen*, and k has been redefined to be *outlen* in order to be consistent with the other DRBGs.

The specifications for the **MS_DRBG** (see Section 10.3.3.2) allow e and k (i.e., *outlen*) to be specified. The lengths *seedlen* and *outlen*, the RSA modulus n , and the value of the exponent e are variable within the bounds described below. The bounds are based on the desired *security strength* for the bits produced. For maximum efficiency, e **should** be kept small and *outlen* **should** be large. The *outlen* bits generated at each step are concatenated to form pseudorandom bitstrings of any desired length. Table 6 provides definitions for using with the **MS_DRBG** functions and algorithms.

Table 6: Definitions for MS_DRBG

	$\lg(n) = 2048$	$\lg(n) = 3072$
Supported security strengths	112	112, 128
<i>highest_supported_security_strength</i>	112	128
Output Block Length (<i>outlen</i> = k)	$8 \leq \text{outlen} \leq \min\{\lg(n) - 2*\text{security_strength}, \lg(n) - 2*\lg(n)/e\}$	
Required minimum entropy for instantiate and reseed		<i>Security_strength</i>
Minimum entropy input length (<i>min_entropy_input_length</i>)		<i>security_strength</i>
Maximum entropy input length (<i>max_entropy_input_length</i>)		$\leq 2^{13}$ bits
Maximum personalization string length (<i>max_personalization_string_length</i>)		$\leq 2^{13}$ bits
Maximum additional_input_length (<i>max_additional_input_length</i>)		$\leq 2^{13}$ bits
Number of hard bits ($\lg(\lg(n))$)	11	11
Seed length (<i>seedlen</i> = r)		$\lg(n) - \text{outlen}$
Appropriate hash functions	SHA-1, SHA-224, SHA-256, SHA-384, SHA-512	
<i>max_number_of_bits_per_request</i>	$\text{outlen} \times \text{reseed_interval}$	
Number of blocks of <i>outlen</i> between reseeds (<i>reseed_interval</i>)	$\leq 50,000$ blocks	

10.3.3.2 MS_DRBG Specifications

10.3.3.2.1 Internal State for MS_DRBG

The internal state for MS_DRBG consists of:

1. The *working_state*:
 - a. The M-S parameters n , e , $seedlen$ and $outlen$, and
 - b. An integer S in $[0, 2^{seedlen}]$ that propagates the internal state sequence from which pseudorandom bits are derived.
 - c. A counter (*block_counter*) that indicates the number of blocks of random produced by MS_DRBG during the current instance since the previous reseeding.
2. Administrative information:
 - a. The *security_strength* provided by the instance of the DRBG, and
 - b. A *prediction_resistance_flag* that indicates whether prediction resistance is required by the DRBG.

The value of S is the critical value of the internal state upon which the security of this DRBG depends (i.e., s is the “secret value” of the internal state).

10.3.3.2.2 Selection of the M-S parameters

The instantiation of MS_DRBG consists of selecting an appropriate RSA modulus n and exponent e ; sizes $seedlen$ and $outlen$ for the seeds and output strings, respectively; and a starting seed.

The M-S parameters n , $seedlen$, e and $outlen$ are selected to satisfy the following six conditions, based on *strength*:

- | | |
|--|---|
| 1. $1 < e < \phi(n)$; $\gcd(e, \phi(n)) = 1$. | Comment: ensures that the mapping $s \rightarrow s^e \pmod{n}$ is 1-1. |
| 2. $(e \times seedlen) \geq 2 * \lg(n)$. | Comment: ensures that the exponentiation requires a full modular reduction. |
| 3. $seedlen \geq 2 * security_strength$. | Comment: protects against a tableization attack. |
| 4. $outlen$ and $seedlen$ are multiples of 8. | Comment: This is an implementation convenience. |
| 5. $outlen \geq 8$; $seedlen + outlen = \lg(n)$. | Comment: all bits are used. |
| 6. $n = p * q$. | Comment: p and q are strong [as in FIPS 186- |

3], secret primes .

The M-S parameters are determined in this order:

1. The size of the modulus $\lg(n)$ is set first. It **shall** conform to the values given in Table 6 for the requested *security_strength*.
2. The RSA exponent e . The implementation **should** allow the application to request any odd integer e in the range $1 < e < 2^{\lg(n)-1} - 2^{*\frac{1}{2}\lg(n)}$. [Comment: The inequality ensures that $e < \phi(n)$ when an Approved algorithm is used to generate the primes p and q .] If e is not provided during an instantiate request, or *requested_e* = 0 is supplied, the default value $e=3$ **should** be used.
3. The number *outlen* of output bits used for each iteration. The implementation **should** allow any multiple of 8 in the range $8 \leq \text{outlen} \leq \min\{\lg(n) - 2*\text{security_strength}, \lg(n) - 2^{*\lg(n)/e}\}$ to be requested. However, if a value for *outlen* is not provided or *requested_outlen* = 0 is specified, *outlen* **should** be selected as the *largest* multiple of 8 integer in the allowable range **and** within the range of bits currently known to be *hard* bits for the RSA problem. That value is $\lg(\lg(n))$, as shown in Table 6. Thus, in all cases, the default value 8 will be used if *requested_outlen* = 0.
Any values for *requested_e* and *requested_outlen* outside these ranges **shall** be flagged as **errors**.
4. Set the size of the seeds: $\text{seedlen} = \lg(n) - \text{outlen}$.
5. Selection of the modulus n . Two primes p and q of size $\frac{1}{2}\lg(n)$ bits, having entropy at least *min_entropy*, and satisfying $\gcd(e, (p-1)(q-1)) = 1$ **shall** be generated as specified in FIPS 186-3. An implementation **shall** use strong primes as defined in that document: each of $p-1, p+1, q-1, q+1$ **shall** have a large prime factor of at least *security_strength* bits. [Comment: Any Approved algorithm will generate a modulus of size $\lg(n)$ bits using strong primes of size $\frac{1}{2}\lg(n)$ bits, and will allow the exponent e to be specified beforehand.]

Comment [ebb5]: Page: 91
For DSS, $16,537 < e < (2^{nlen-2s}-1)$, where *nlen* is the length of n , and *s* is the security strength.

The difficulty of the RSA problem relies on the secrecy of the primes p and q comprising the modulus. Whenever private primes are generated, the implementation **shall** clear memory of those values immediately after n has been computed. Only the modulus n **shall** be kept in the internal *state*.

10.3.3.2.3 Instantiation of MS_DRBG

Notes for the instantiate function:

The instantiation of **MS_DRBG** requires a call to the instantiate function specified in Section 9.2; step 8 of that function calls the instantiate algorithm in this section. For this DRBG, two DRBG-specific input parameters may be provided: *requested_e* and *requested_outlen*.

The values for *highest_supported_security_strength* and *min_entropy_input_length*

are provided in Table 6 in Section 10.3.3.1.

In step 5 of the instantiate function, the following steps **shall** be used to select values for n , e , $seedlen$ and $outlen$:

5. Using $security_strength$, $requested_e$ (if provided) and $requested_outlen$ (if provided), select values for n , e , $seedlen$ and $outlen$.

Comment: Determine the modulus size.

- 5.1 If $security_strength = 112$, then $\lg(n) = 2048$

Else $\lg(n) = 3072$.

Comment: Select the exponent e .

- 5.2 If $requested_e < 65537$ or is not provided, then $e = 65537$

Else

- 5.2.1 $e = requested_e$.

- 5.2.2 If ($requested_e < 3$) or ($requested_e > 2^{\lfloor \lg(n) \rfloor - 1} - (2 \times 2^{1/2 \lfloor \lg(n) \rfloor})$) or ($requested_e$ is even), then return an **ERROR**.

Comment : Select the output length $outlen$.

- 5.3 If $requested_outlen = 0$ or is not provided, then $outlen = 8$

Else

- 5.3.1 $outlen = requested_outlen$.

- 5.3.2 If ($outlen < 1$) or ($outlen > \min(\lfloor \lg(n) \rfloor - 2 \times security_strength, \lfloor \lg(n) \times (1 - 2/e) \rfloor)$) or ($outlen$ is not a multiple of 8), then return an **ERROR**.

Comment : Determine the seed length ($seedlen$).

- 5.4 $seedlen = \lg(n) - outlen$.

Comment: Get the modulus n .

- 5.5 Using $\lg(n)$ and e , get a random modulus n . n **shall** be the product of two primes p and q such that :

- 1) Each has a length of $\lg(n)/2$ bits,
- 2) Each has at least $security_strength + 64$ bits of entropy,
- 3) $\gcd(e, (p-1), (q-1)) = 1$.
- 4) $(p-1), (p+1), (q-1)$ and $(q+1)$ **shall** each have a large prime factor of at least $security_strength$ bits.

5.6 $n = p \times q$.

5.7 $p = q = 0$.

Since the values for *working_state* values n , e , and $outlen$ have been determined by step 5 (above), they need not be provided to nor returned from the instantiate algorithm in step 9; however, the value of *seedlen* is required by the instantiate algorithm and must be provided to it.

The instantiate algorithm:

Let **Hash** (...) be an Approved hash function for the security strengths to be supported.

The following process or its equivalent **shall** be used as the instantiate algorithm for this DRBG (see step 9 in Section 9.2):

Input:

1. *entropy_input*: The string of bits obtained from the entropy input source.
2. *nonce*: A string of bits as specified in Section 8.5.2.
3. *personalization_string*: The personalization string received from the consuming application.
4. *seedlen*: The length of the seed.

Output:

1. *working_state*: The initial values for S and *block_counter* (see Section 10.3.3.2.1).

Process:

1. *seed_material* = *entropy_input* || *nonce* || *personalization_string*.
2. $S = \text{Hash_df}(\text{seed_material}, \text{seedlen})$.
3. *block_counter* = 0.
4. Return **SUCCESS**, S and *block_counter* for the *working_state*.

Implementation notes:

If a *personalization_string* will never be provided, then steps 1 and 2 may be combined as follows:

$S = \text{Hash_df}(\text{entropy_input}, \text{seedlen})$.

10.3.3.2.4 Reseeding of a MS_DRBG Instantiation

Notes for the reseed function:

The reseed of **MS_DRBG** requires a call to the reseed function specified in Section 9.3; step 5 of that function calls the reseed algorithm in this section. The values for *min_entropy_input_length* are provided in Table 6 of Section 10.3.3.1.

The reseed algorithm:

Let **Hash_df** be the hash derivation function specified in Section 9.6.2 using an appropriate hash function from Table 6 in Section 10.3.3.1.

The following process or its equivalent **shall** be used as the reseed algorithm for this DRBG (see step 5 of Section 9.3):

Input:

1. *working_state*: The current values for *seedlen* and *S*.
2. *entropy_input*: The string of bits obtained from the entropy input source.
3. *additional_input*: The additional input string received from the consuming application.

Output:

1. *status*: The status of performing this algorithm. For this DRBG, the only status is **SUCCESS**.
2. *working_state*: The new values for *S* and *block_counter*.

Process:

1. *seed_material* = *S* || *entropy_input* || *additional_input*.
2. *S* = **Hash_df** (*seed_material*, *seedlen*).
3. *block_counter* = 0.
4. Return **SUCCESS**, and the new values of *S* and *block_counter*.

Implementation notes:

If *additional_input* will never be provided, then steps 1 may be modified as follows:

seed_material = *S* || *entropy_input*.

10.3.3.2.5 Generating Pseudorandom Bits Using MS_DRBG

Notes for the generate function:

The generation of pseudorandom bits using an **MS_DRBG** instantiation requires a call to the generate function specified in Section 9.4; step 8 of that function calls the generate algorithm specified in this section. The values for *max_number_of_bits_per_request* and *outlen* are provided in Table 6 of Section 10.3.3.1.

The generate algorithm:

Let **Hash_df** be the hash derivation function specified in Section 9.6.2 using an appropriate hash function from Table 6 in Section 10.3.3.1. The value of *reseed_interval* is also specified in Table 6.

Let **pad8** (*bitstring*) be a function that inputs an arbitrary length *bitstring* and returns a copy of that *bitstring* padded on the right with binary 0's, if necessary, to a multiple of 8. Note: This is an implementation convenience for byte-oriented functions.

Let **Truncate** (*bits*, *in_len*, *out_len*) be a function that inputs a bitstring of *in_len* bits, returning a string consisting of the leftmost *out_len* bits of input. If *in_len* < *out_len*, the input string is returned padded on the right with *out_len* - *in_len* zeroes.

The following process or its equivalent **shall** be used to generate pseudorandom bits (see step 8 in Section 9.4):

Input:

1. *working_state*: The current values for *n*, *e*, *seedlen*, *outlen*, *S*, and *reseed_counter* (see Section 10.3.3.2.1).
2. *requested_number_of_bits*: The number of pseudorandom bits to be returned to the generate function.
3. *additional_input*: The additional input string received from the consuming application.

Output:

1. *status*: The status returned from the function. The *status* will indicate **SUCCESS** or indicate that a reseed is required before the requested pseudorandom bits can be generated. In the latter case, either nothing but the reseed indication **shall** be returned as output, or a *Null* string **shall** be returned as the *returned_bits* (see below).
2. *returned_bits*: The pseudorandom bits to be returned to the generate function.
3. *S*: The updated secret value in the *working_state*.
4. *block_counter*: The updated block counter for reseeding.

Process:

Comment: Check whether a reseed is required.

1. If $\left(\text{block_counter} + \left\lceil \frac{\text{requested_number_of_bits}}{\text{outlen}} \right\rceil \right) > \text{reseed_interval}$, then return an indication that a reseed is required.
2. If (*additional_input* = *Null*) then *additional_input* = 0

Comment: *additional_input* set to *seedlen* zeroes.

Else *additional_input* = **Hash_df** (**pad8** (*additional_input_string*), *seedlen*).

- Comment: Hash to *seedlen* bits.
- Comment: Produce *requested_number_of_bits*, *outlen* at a time.
3. *temp* = the Null string.
 4. *i* = 0.
 5. *s* = *S* \oplus *additional_input*.
Comment: *s* is to be interpreted as a *seedlen*-bit unsigned integer.
 6. $S = \lfloor (s^e \bmod n) / 2^{outlen} \rfloor$
Comment: *S* is a *seedlen*-bit number.
 7. $R = (s^e \bmod n) \bmod 2^{outlen}$
Comment: *R* is an *outlen*-bit number.
 8. *temp* = *temp* || *R*.
 9. *additional_input* = 0^{*seedlen*}.
Comment: *seedlen* zeroes.
 10. *i* = *i* + 1.
 11. *block_counter* = *block_counter* + 1.
 12. If (**len** (*temp*) < *requested_number_of_bits*), then go to step 6.
 13. *returned_bits* = **Truncate** (*temp*, *i* \times *k*, *requested_number_of_bits*).
 14. Return **SUCCESS**, *returned_bits* and the values of *S* and *block_counter* for the *working_state*.

11 Assurance

11.1 Overview

A user of a DRBG for cryptographic purposes requires assurance that the generator actually produces random and unpredictable bits. The user needs assurance that the design of the generator, its implementation and its use to support cryptographic services are adequate to protect the user's information. In addition, the user requires assurance that the generator continues to operate correctly. The assurance strategy for the DRBGs in this standard is depicted in Figure 18.

The design of each DRBG in this standard has received an evaluation of its security properties prior to its selection for inclusion in this Standard.

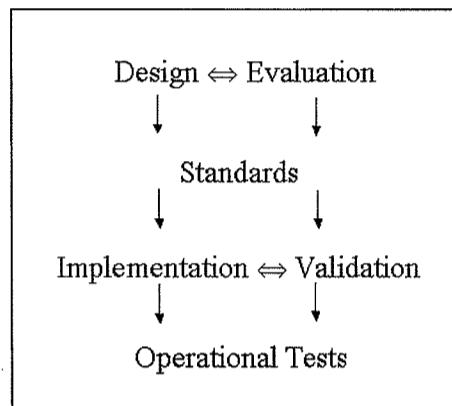


Figure 18: DRBG Assurance Strategy

The accuracy of an implementation of a DRBG process **may** be asserted by an implementer, but this Standard requires the development of basic documentation to provide minimal assurance that the DRBG process has been implemented properly (see Section 11.2). An implementation **should** be validated for conformance to this Standard by an accredited laboratory (see Section 11.3). Such validations provide a higher level of assurance that the DRBG is correctly implemented. Validation testing for DRBG processes consists of testing whether or not the DRBG process produces the expected result, given a specific set of input parameters (e.g., entropy input). Implementations used directly by consuming applications **should** also be validated against conformance to FIPS 140-2.

Operational (i.e., health) tests on the DRBG **shall** be implemented within a DRBG boundary or sub-boundary in order to determine that the process continues to operate as designed and implemented. See Section 11.4 for further information.

A cryptographic module containing a DRBG **should** be validated (see FIPS 140-2 [8]). The consuming application or cryptographic service that uses a DRBG **should** also be validated and periodically tested for continued correct operation. However, this level of testing is outside the scope of this Standard.

Note that any entropy input used for testing (either for validation testing or operational/health testing) may be publicly known. Therefore, entropy input used for testing **shall not** knowingly be used for normal operational use.

11.2 Minimal Documentation Requirements

This Standard requires the development of a set of documentation that will provide assurance to users and (optionally) validators that the DRBGs in this Standard have been implemented properly. Much of this documentation may be placed in a user's manual. This documentation **shall** consist of the following as a minimum:

- Document how the implementation has been designed to permit implementation validation and operational testing.
- Document the type of DRBG (e.g., Hash_DRBG, Dual_EC_DRBG), and the cryptographic primitives used (e.g., SHA-256, AES-128).
- Document the security strengths supported by the implementation.
- Document features supported by the implementation (e.g., prediction resistance, the available elliptic curves, etc.).
- In the case of the CTR_DRBG and OFB_DRBG, indicate whether a derivation function is provided. If a derivation function is not used, documentation **shall** clearly indicate that the implementation can only be used when full entropy input is available.
- Document any support functions other than operational testing.

Comment [ebb6]: Page: 98
Probably need to add additional documentation requirements to address other requirements.

11.3 Implementation Validation Testing

A DRBG process **may** be tested for conformance to this Standard. Regardless of whether or not validation testing is obtained by an implementer, a DRBG **shall** be designed to be tested to ensure that the product is correctly implemented; this will allow validation testing to be obtained by a consumer, if desired. A testing interface **shall** be available for this purpose in order to allow the insertion of input and the extraction of output for testing.

Implementations to be validated **shall** include the following:

- Documentation specified in Section 11.2.
- Any documentation or results required in derived test requirements.

11.4 Operational/Health Testing

11.4.1 Overview

A DRBG implementation **shall** perform self-tests to ensure that the DRBG continues to function properly. Self-tests of the DRBG processes **shall** be performed prior to the first instantiation and periodically, and a capability to perform self-tests on demand **shall** be included (see Section 9.7). A DRBG implementation may optionally perform other self-tests for DRBG functionality in addition to the tests specified in this Standard.

All data output from the DRBG boundary **shall** be inhibited while these tests are performed. The results from known-answer-tests (see Section 11.4.2) **shall not** be output

as random bits during normal operation.

When a DRBG fails a self-test, the DRBG **shall** enter an error state and output an error indicator. The DRBG **shall not** perform any DRBG operations while in the error state, and no pseudorandom bits **shall** be output when an error state exists. When in an error state, user intervention (e.g., power cycling, restart of the DRBG) **shall** be required to exit the error state (see Sections 7.2.7 and 9.8).

11.4.2 Known Answer Testing

Known answer testing **shall** be conducted prior to the first instantiation and periodically, and may be conducted on demand. A known-answer test involves operating the DRBG with data for which the correct output is already known and determining if the calculated output equals the expected output (the known answer). The test fails if the calculated output does not equal the known answer. In this case, the DRBG **shall** enter an error state and output an error indicator (see Sections 7.2.7 and 9.8).

The generalized known answer testing is specified in Section 9.7. Testing **shall** be performed on all DRBG functions implemented.

Annex A: (Normative) Application-Specific Constants

A.1 Constants for the Dual_EC_DRBG

The **Dual_EC_DRBG** requires the specifications of an elliptic curve and two points on the elliptic curve. One of the following NIST approved curves and points **shall** be used in applications requiring certification under FIPS 140-2. More details about these curves may be found in FIPS PUB 186-3, the Digital Signature Standard.

A.1.1 Curves over Prime Fields

Each of following mod p curves is given by the equation:

$$y^2 = x^3 - 3x + b \pmod{p}$$

Notation:

p - Order of the field F_p , given in decimal

r - order of the Elliptic Curve Group, in decimal. Note that r is used here for consistency with FIPS 186-3 but is referred to as n in the description of the **Dual_EC_DRBG (...)**

b - coefficient above

The x and y coordinates of the base point, ie generator G , are the same as for the point P .

A.1.1.1 Curve P-224

$p = 26959946667150639794667015087019630673557916\backslash$
260026308143510066298881

$r = 26959946667150639794667015087019625940457807\backslash$
714424391721682722368061

$b = b4050a85 0c04b3ab f5413256 5044b0b7 d7bfd8ba 270b3943$
2355ffb4

$Px = b70e0cbd 6bb4bf7f 321390b9 4a03c1d3 56c21122 343280d6$
115c1d21

$Py = bd376388 b5f723fb 4c22dfe6 cd4375a0 5a074764 44d58199$
85007e34

ANS X9.82, Part 3 - DRAFT - March 2005

$Q_x = 68623591\ 6e11adfa\ f080a451\ 477fa27a\ f21248be\ 916d3458\ a583a3c9$

$Q_y = 6060018a\ 24b35be6\ caecf3f0\ 7f2c6b43\ 4e47479e\ 55362c8f\ 5707adca$

A.1.1.2 Curve P-256

$p = 11579208921035624876269744694940757353008614\ \backslash 3415290314195533631308867097853951$

$r = 11579208921035624876269744694940757352999695\ \backslash 5224135760342422259061068512044369$

$b = 5ac635d8\ aa3a93e7\ b3ebbd55\ 769886bc\ 651d06b0\ cc53b0f6\ 3bce3c3e\ 27d2604b$

$P_x = 6b17d1f2\ e12c4247\ f8bce6e5\ 63a440f2\ 77037d81\ 2deb33a0\ f4a13945\ d898c296$

$P_y = 4fe342e2\ fe1a7f9b\ 8ee7eb4a\ 7c0f9e16\ 2bce3357\ 6b315ece\ cbb64068\ 37bf51f5$

$Q_x = c97445f4\ 5cdef9f0\ d3e05e1e\ 585fc297\ 235b82b5\ be8ff3ef\ ca67c598\ 52018192$

$Q_y = b28ef557\ ba31dfcb\ dd21ac46\ e2a91e3c\ 304f44cb\ 87058ada\ 2cb81515\ 1e610046$

A.1.1.3 Curve P-384

$p = 39402006196394479212279040100143613805079739\ \backslash 27046544666794829340424572177149687032904726\ \backslash 6088258938001861606973112319$

$r = 39402006196394479212279040100143613805079739\ \backslash 27046544666794690527962765939911326356939895\ \backslash 6308152294913554433653942643$

$b = b3312fa7\ e23ee7e4\ 988e056b\ e3f82d19\ 181d9c6e\ fe814112\ 0314088f\ 5013875a\ c656398d\ 8a2ed19d\ 2a85c8ed\ d3ec2aef$

$P_x = aa87ca22\ be8b0537\ 8eb1c71e\ f320ad74\ 6e1d3b62\ 8ba79b98\ 59f741e0\ 82542a38\ 5502f25d\ bf55296c\ 3a545e38\ 72760ab7$

$P_y = 3617de4a\ 96262c6f\ 5d9e98bf\ 9292dc29\ f8f41dbd\ 289a147c\ 101$

ANS X9.82, Part 3 - DRAFT - March 2005

e9da3113 b5f0b8c0 0a60b1ce 1d7e819d 7a431d7c 90ea0e5f

$Q_x = 8e722de3\ 125bddb0\ 5580164b\ fe20b8b4\ 32216a62\ 926c5750$

$2cede31\ c47816ed\ d1e89769\ 124179d0\ b6951064\ 28815065$

$Q_y = 023b1660\ dd701d08\ 39fd45ee\ c36f9ee7\ b32e13b3\ 15dc0261$

$0aa1b636\ e346df67\ 1f790f84\ c5e09b05\ 674dbb7e\ 45c803dd$

A.1.1.4 Curve P-521

$p = 68647976601306097149819007990813932172694353\backslash$

$00143305409394463459185543183397656052122559\backslash$

$64066145455497729631139148085803712198799971\backslash$

$6643812574028291115057151$

$r = 68647976601306097149819007990813932172694353\backslash$

$00143305409394463459185543183397655394245057\backslash$

$74633321719753296399637136332111386476861244\backslash$

$0380340372808892707005449$

$b = 051953eb\ 9618e1c9\ a1f929a2\ 1a0b6854\ 0eea2da7\ 25b99b31$

$5f3b8b48\ 9918ef10\ 9e156193\ 951ec7e9\ 37b1652c\ 0bd3bb1b$

$f073573d\ f883d2c3\ 4f1ef451\ fd46b503\ f00$

$P_x = c6858e06\ b70404e9\ cd9e3ecb\ 662395b4\ 429c6481\ 39053fb5$

$21f828af\ 606b4d3d\ baa14b5e\ 77efe759\ 28feldc1\ 27a2ffa8$

$de3348b3\ c1856a42\ 9bf97e7e\ 31c2e5bd\ 66$

$P_y = 11839296\ a789a3bc\ 0045c8a5\ fb42c7d1\ bd998f54\ 449579b4$

$46817afb\ d17273e6\ 62c97ee7\ 2995ef42\ 640c550b\ 9013fad0$

$761353c7\ 086a272c\ 24088be9\ 4769fd16\ 650$

$Q_x = 1b9fa3e5\ 18d683c6\ b6576369\ 4ac8efba\ ec6fab44\ f2276171$

$a4272650\ 7dd08add\ 4c3b3f4c\ 1ebc5b12\ 22ddba07\ 7f722943$

$b24c3edf\ a0f85fe2\ 4d0c8c01\ 591f0be6\ f63$

$Q_y = 1f3bdb45\ 85295d9a\ 1110d1df\ 1f9430ef\ 8442c501\ 8976ff34\ 37ef91b8\ 1dc0b813$

$2c8d5c39\ c32d0e00\ 4a3092b7\ d327c0e7\ a4d26d2c\ 7b69b58f\ 90666529\ 11e45777\ 9de$

A.1.2 Curves over Binary Fields

For each field degree m , a pseudo-random curve (B) and a Koblitz curve (K) are given.

The pseudo-random curve has the form

$$E: y^2 + xy = x^3 + x^2 + b,$$

and the Koblitz curve has the form

$$E: y^2 + xy = x^3 + ax^2 + 1, \text{ where } a = 0 \text{ or } 1.$$

For each pseudorandom curve, the cofactor is $f = 2$. The cofactor of each Koblitz curve is $f = 2$ if $a = 1$, and $f = 4$ if $a = 0$.

The coefficients of the pseudo-random curves, and the coordinates of the points P and Q for both kinds of curves, are given in terms of both the polynomial and normal basis representations, in hex.

NOTE: An implementation may choose to represent coordinates in either basis. However, in order to gain certification it must demonstrate agreement with the test output vectors, which have been generated using the normal basis representation for each of the binary curves.

The order r of the base point P is given in decimal.

Note that r is used here for consistency with FIPS 186-3 but is referred to as n in the description of the **Dual_EC_DRBG()**. r is given in decimal

A.1.2.1 Curve K-233

```
a = 0
r = 34508731733952818937173779311385127605709409888622521\
      26328087024741343
```

Polynomial Basis:

```
Px = 00000172 32ba853a 7e731af1 29f22ff4 149563a4 19c26bf5
      0a4c9d6e efad6126
Py = 000001db 537dece8 19b7f70f 555a67c4 27a8cd9b f18aeb9b
      56e0c110 56fae6a3
```

Normal Basis:

```
Px = 000000fd e76d9dc0 26e643ac 26f1aa90 1aa12978 4b71fc07
      22b2d056 14d650b3
Py = 00000064 3e317633 155c9e04 47ba8020 a3c43177 450ee036
      d6335014 34cac978
```

Polynomial Basis:

```
Qx = 000000aa 7178e973 8a6f797a 1c265465 06106896 0a58b3fe
      a3afc77f 18404eee
Qy = 0000002d 12a8f3e9 884bf31d 052a8eaf 414b891a 0a40491e
      1f9d2576 79248ee2
```

ANS X9.82, Part 3 - DRAFT - March 2005

Normal Basis:

$Qx = 0000015a\ 96493d91\ e56b5f10\ 579a7d58\ eb895e06\ 8d94e1af$

$86d34143\ 4377548c$

$Qy = 0000006b\ 13a689bb\ 3730dfd7\ a46486ea\ ff8eb6cb\ 9d815981$

$a927d2eb\ 8cfa9b00$

A.1.2.3 Curve B-233

$r = 69017463467905637874347558622770255558398127373450135\$

55379383634485463

Polynomial Basis:

$b = 066\ 647ede6c\ 332c7f8c$

$0923bb58\ 213b333b\ 20e9ce42\ 81fe115f\ 7d8f90ad$

$Px = 000000fa\ c9dfcbac\ 8313bb21\ 39f1bb75\ 5fef65bc\ 391f8b36$

$f8f8eb73\ 71fd558b$

$Py = 00000100\ 6a08a419\ 03350678\ e58528be\ bf8a0bef\ f867a7ca$

$36716f7e\ 01f81052$

Normal Basis:

$b = 1a0\ 03e0962d\ 4f9a8e40$

$7c904a95\ 38163adb\ 82521260\ 0c7752ad\ 52233279$

$Px = 0000018b\ 863524b3\ cdfebf94\ f2784e0b\ 116faac5\ 4404bc91$

$62a363ba\ b84a14c5$

$Py = 00000049\ 25df77bd\ 8b8ff1a5\ ff519417\ 822bfedf\ 2bbd7526$

$44292c98\ c7af6e02$

Polynomial Basis:

$Qx = 000000cb\ 50ce04af\ f4ea6111\ aaccfe04\ ae5f0dfe\ 95a59db4$

$cd4aba0c\ 1126615a$

$Qy = 0000005b\ ab8a93a0\ 5c42caa1\ 1b322b14\ 876ec2e0\ 5c994a25$

$8e67295e\ 5808eaf9$

Normal Basis:

$Qx = 00000055\ ea07c1ca\ 4a4312f3\ 4562737c\ 257f4fa8\ 3b9d3d48$

$8a123cab\ 238f69a2$

$Qy = 00000055\ d60ea17a\ 1cb969a8\ 3786a82f\ 8172e889\ 026195f9$

ANS X9.82, Part 3 - DRAFT - March 2005

923ba4b1 beeb5702

A.1.2.2 Curve K-283

$a = 0$

$r = 38853377844514581418389238136470378132848117337930613 \backslash$
 $24295874997529815829704422603873$

Polynomial Basis:

$P_x = 0503213f\ 78ca4488\ 3f1a3b81\ 62f188e5\ 53cd265f\ 23c1567a$
 $16876913\ b0c2ac24\ 58492836$

$P_y = 01ccda38\ 0f1c9e31\ 8d90f95d\ 07e5426f\ e87e45c0\ e8184698$
 $e4596236\ 4e341161\ 77dd2259$

Normal Basis:

$P_x = 03ab9593\ f8db09fc\ 188f1d7c\ 4ac9fcc3\ e57fcfd3b\ db15024b$
 $212c7022\ 9de5fcfd9\ 2eb0ea60$

$P_y = 02118c47\ 55e7345c\ d8f603ef\ 93b98b10\ 6fe8854f\ feb9a3b3$
 $04634cc8\ 3a0e759f\ 0c2686b1$

Polynomial Basis:

$Q_x = 0388eeee4\ 1cc5808d\ 140d5179\ 76fba0fa\ 9c14b886\ 914387a6$
 $890a9497\ fd3370b6\ 9cdd3779$

$Q_y = 04d86b99\ fed2ecad\ 1dc9fd77\ ed5928ac\ ef908f97\ 1eb22cf6$
 $8e436df4\ dbe6e06e\ b2c2dff4$

Normal Basis:

$Q_x = 004ab17d\ 72374eb7\ dac733d8\ 83d7b650\ eb03ccb9\ d6c60197$
 $74f41ef2\ 1b8e0e11\ 0fe8aa58$

$Q_y = 07243a25\ e2e7e633\ 7897e8b1\ 9791c813\ 0317aecf\ 8c0ac2a4$
 $2ac03dac\ 4afdbae8\ ffc9888c$

A.1.2.4 Curve B-283

$r = 77706755689029162836778476272940756265696259243769048 \backslash$
 $89109196526770044277787378692871$

Polynomial Basis:

$b = 27b680a\ c8b8596d\ a5a4af8a\ 19a0303f$
 $ca97fd76\ 45309fa2\ a581485a\ f6263e31\ 3b79a2f5$

$P_x = 05f93925\ 8db7dd90\ e1934f8c\ 70b0dfec\ 2eed25b8\ 557eac9c$

ANS X9.82, Part 3 - DRAFT - March 2005

80e2e198 f8cdbecd 86b12053

$P_y = 03676854\ fe24141c\ b98fe6d4\ b20d02b4\ 516ff702\ 350eddb0$
 $826779c8\ 13f0df45\ be8112f4$

Normal Basis:

$b = 157261b\ 894739fb\ 5a13503f\ 55f0b3f1$
 $0c560116\ 66331022\ 01138cc1\ 80c0206b\ dafbc951$

$P_x = 0749468e\ 464ee468\ 634b21f7\ f61cb700\ 701817e6\ bc36a236$
 $4cb8906e\ 940948ea\ a463c35d$

$P_y = 062968bd\ 3b489ac5\ c9b859da\ 68475c31\ 5baafcde\ ccd0dc90$
 $5b70f624\ 46f49c05\ 2f49c08c$

Polynomial Basis:

$Q_x = 06530328\ 33283d9e\ b6ebc03c\ 2d735ed9\ 12b46bc1\ 2e364643$
 $f8e309d9\ d55e9440\ 28190ba5$

$Q_y = 03693cd3\ 8b4e022d\ ef81bb7f\ 949ca7f4\ 287cbc3d\ 3aae8632$
 $a6fea719\ e0da9998\ 48211443$

Normal Basis:

$Q_x = 06c2366c\ 8acc000a\ 5b516dfc\ 4cf8a204\ b255dd0d\ e53f18e1$
 $99718e05\ 47b3845f\ 000626c9$

$Q_y = 03667f53\ e1e528e9\ 99bf2cb\ 9e609116\ 969d78fb\ 94a264a9$
 $a2045878\ 132ca8f5\ 85b874ef$

A.1.2.5 Curve K-409

$a = 0$

$r = 33052798439512429947595765401638551991420234148214060\$
 $96423243950228807112892491910506732584577774580140963\$
 66590617731358671

Polynomial Basis:

$P_x = 0060f05f\ 658f49c1\ ad3ab189\ 0f718421\ 0efd0987\ e307c84c$
 $27accfb8\ f9f67cc2\ c460189e\ b5aaaa62\ ee222eb1\ b35540cf$
 $e9023746$

$P_y = 01e36905\ 0b7c4e42\ acbaldac\ bf04299c\ 3460782f\ 918ea427$
 $e6325165\ e9ea10e3\ da5f6c42\ e9c55215\ aa9ca27a\ 5863ec48$
 $d8e0286b$

Normal Basis:

```
Px = 01b559c7 cba2422e 3affe133 43e808b5 5e012d72 6ca0b7e6  
a63aaefb cle3a98e 10ca0fcf 98350c3b 7f89a975 4a8e1dc0  
713cec4a  
Py = 016d8c42 052f07e7 713e7490 eff318ba 1abd6fef 8a5433c8  
94b24f5c 817aeb79 852496fb ee803a47 bc8a2038 78ebf1c4  
99af7d6
```

Polynomial Basis:

```
Qx = 01ba9a6c 2d31edf6 671ce7d1 f16f4ab2 7c72ca88 cc3b33e9  
b2ef536e 92bc06ad 0cac0d6a 821898c2 847b5d7e 8506fd26  
9e51dfcc  
Qy = 019d9567 d1931672 ab748567 c4fb75a4 e0658b9b bf17901e  
b7d41148 489ab481 354977ac 390bbb05 a6e782b5 13caa159  
02a846ef
```

Normal Basis:

```
Qx = 00e8b595 6a3f2ec5 e8e3e3cf e4c2003a 687feecc ade301e5  
c34d47ef a723dac6 36f1ef6a cd5ced42 309fc937 fa5460d5  
223c3743  
Qy = 001f61f2 2a66d942 de111925 dd94da7d 5c02e4c2 23328be5  
9019a157 d7b700f6 d8b42316 efe8193d 68c90ce0 fe57ad2b  
4f690281
```

A.1.2.6 Curve B-409

```
r = 66105596879024859895191530803277103982840468296428121\  
92846487983041577748273748052081437237621791109659798\  
67288366567526771
```

Polynomial Basis:

```
b = 021a5c2 c8ee9feb 5c4b9a75  
3b7b476b 7fd6422e f1f3dd67 4761fa99 d6ac27c8  
a9a197b2 72822f6c d57a55aa 4f50ae31 7b13545f
```

```
Px = 015d4860 d088ddb3 496b0c60 64756260 441cde4a f1771d4d  
b01ffe5b 34e59703 dc255a86 8a118051 5603aeab 60794e54  
bb7996a7  
Py = 0061b1cf ab6be5f3 2bbfa783 24ed106a 7636b9c5 a7bd198d  
0158aa4f 5488d08f 38514f1f df4b4f40 d2181b36 81c364ba  
0273c706
```

ANS X9.82, Part 3 - DRAFT - March 2005

Normal Basis:

$b = 124d065\ 1c3d3772\ f7f5a1fe$
 $6e715559\ e2129bdf\ a04d52f7\ b6ac7c53\ 2cf0ed06$
 $f610072d\ 88ad2fdc\ c50c6fde\ 72843670\ f8b3742a$

$P_x = 00ceacbc\ 9f475767\ d8e69f3b\ 5dfab398\ 13685262\ bcacf22b$
 $84c7b6dd\ 981899e7\ 318c96f0\ 761f77c6\ 02c016ce\ d7c548de$
 $830d708f$

$P_y = 0199d64b\ a8f089c6\ db0e0b61\ e80bb959\ 34af0ca\ f2e8be76$
 $d1c5e9af\ fc7476df\ 49142691\ ad303902\ 88aa09bc\ c59c1573$
 $aa3c009a$

Polynomial Basis:

$Q_x = 01920ed2\ 5ec895fc\ 704ac0da\ 05a93ace\ 25fc9646\ ab4533c0$
 $4f759ce1\ ac0e53d8\ 096b2318\ d6fdd0d7\ 1d2affd6\ 915e8d7a$
 $e2977127$

$Q_y = 011d1d15\ 0c127a29\ 77b48a17\ fac8aa13\ 96985213\ 3179fc17$
 $74f9d3db\ 1f6bee43\ d8c04cce\ 35f2abf8\ 022230f6\ 457f260a$
 $72444bfd$

Normal Basis:

$Q_x = 01b2481e\ 3265c48d\ 28db6172\ 95efaf05\ 77f7d0ed\ 175cc49b$
 $0fcbb1982\ 639bc380\ eee80285\ e6ef8a7b\ 1a31566d\ 602c07dc$
 $dc85a5a5$

$Q_y = 00d0712d\ 082d31ba\ 22497958\ b1178993\ a2f5dc41\ f14207e4$
 $0f8ccda8\ 06b637cc\ f1380320\ b6ff9dfd\ 8e811f14\ 49c4c23e$
 $2f4823fe$

A.1.2.7 Curve K-571

$a = 0$
 $r = 19322687615086291723476759454659936721494636648532174\$
 $99328617625725759571144780212268133978522706711834706\$
 $71280082535146127367497406661731192968242161709250355\$
 5733685276673

Polynomial Basis:

$P_x = 026eb7a8\ 59923fbc\ 82189631\ f8103fe4\ ac9ca297\ 0012d5d4$
 $60248048\ 01841ca4\ 43709584\ 93b205e6\ 47da304d\ b4ceb08c$
 $bbdlba39\ 494776fb\ 988b4717\ 4dca88c7\ e2945283\ a01c8972$

ANS X9.82, Part 3 - DRAFT - March 2005

$P_y = 0349dc80\ 7f4fbf37\ 4f4aeade\ 3bca9531\ 4dd58cec\ 9f307a54\ ffc61efc\ 006d8a2c\ 9d4979c0\ ac44aea7\ 4fbbebbb9\ f772aedc\ b620b01a\ 7ba7af1b\ 320430c8\ 591984f6\ 01cd4c14\ 3ef1c7a3$

Normal Basis:

$P_x = 004bb2db\ a418d0db\ 107adae0\ 03427e5d\ 7cc139ac\ b465e593\ 4f0bea2a\ b2f3622b\ c29b3d5b\ 9aa7alfd\ fd5d8be6\ 6057c100\ 8e71e484\ bcd98f22\ bf847642\ 37673674\ 29ef2ec5\ bc3ebcf7$

$P_y = 044ccb57\ de20788d\ 2c952d7b\ 56cf39bd\ 3e89b189\ 84bd124e\ 751ceff4\ 369dd8da\ c6a59e6e\ 745df44d\ 8220ce22\ aa2c852c\ fcbbef49\ ebaa98bd\ 2483e331\ 80e04286\ feaa2530\ 50caff60$

Polynomial Basis:

$Q_x = 06c62ea8\ 63120582\ 6a8e4328\ 412a3400\ 0be7c23f\ 19982e7f\ 35164b12\ c18df503\ 2997173d\ 9776bab1\ 2daf58e\ 97e1aa9d\ 4726eaaa\ 6473c2bc\ 7e0c2752\ fed22ac2\ e86fbfcfc\ 00468dc4$

$Q_y = 070b1c34\ 39bb9845\ 42f21349\ 21ff78d0\ ce6efb9b\ f27f02b5\ 0f83c658\ f29b2076\ ac77c8ac\ 015be59c\ 02d090fb\ 20aa4a35\ f4745614\ 78445d04\ fd2ee388\ 3cbd5508\ f7edcfe7\ a803dd47$

Normal Basis:

$Q_x = 01e8cee5\ 3c73b384\ ad828269\ 7566e3ad\ b11573fd\ 7aff7abd\ 1af60123\ 062e560c\ 1bb66d35\ d00cd77e\ 101e7606\ 6afcd0c9\ 8c8826eb\ 79b91e33\ 1328701c\ 9fb5c3ab\ 01d798af\ c4fbea67$

$Q_y = 079d03ff\ 6f51d98d\ 4679aa59\ 97b51eca\ e2ecf2fe\ ba491edf\ d5df7df7\ 277bb265\ b58b11ad\ 5b916e99\fea7ef78\ 49314df1\ 0af703bd\ 1b202c8c\ fa97760b\ 27044c19\ ac5d9fb5\ 65381df3$

A.1.2.8 Curve B-571

$r = 38645375230172583446953518909319873442989273297064349\ 98657235251451519142289560424536143999389415773083133\ 88112192694448624687246281681307023452828830333241139\ 3191105285703$

Polynomial Basis:

$b = 2f40e7e\ 2221f295\ de297117\ b7f3d62f\ 5c6a97ff\ cb8ceff1\ cd6ba8ce\ 4a9a18ad\ 84ffabbd\ 8efa5933\ 2be7ad67\ 56a66e29\ 4af8185a\ 78ff12aa\ 520e4de7\ 39baca0c\ 7ffe7f\ 2955727a$

ANS X9.82, Part 3 - DRAFT - March 2005

$P_x = 0303001d\ 34b85629\ 6c16c0d4\ 0d3cd775\ 0a93d1d2\ 955fa80a\ a5f40fc8\ db7b2abd\ bde53950\ f4c0d293\ cdd711a3\ 5b67fb14\ 99ae6003\ 8614f139\ 4abfa3b4\ c850d927\ e1e7769c\ 8eec2d19$
 $P_y = 037bf273\ 42da639b\ 6dcffffe\ b73d69d7\ 8c6c27a6\ 009cbbca\ 1980f853\ 3921e8a6\ 84423e43\ bab08a57\ 6291af8f\ 461bb2a8\ b3531d2f\ 0485c19b\ 16e2f151\ 6e23dd3c\ 1a4827af\ 1b8ac15b$

Normal Basis:

$b = 3762d0d\ 47116006\ 179da356\ 88eeaccf\ 591a5cde\ a7500011\ 8d9608c5\ 9132d434\ 26101a1d\ fb377411\ 5f586623\ f75f0000\ 1ce61198\ 3c1275fa\ 31f5bc9f\ 4be1a0f4\ 67f01ca8\ 85c74777$

$P_x = 00735e03\ 5def5925\ cc33173e\ b2a8ce77\ 67522b46\ 6d278b65\ 0a291612\ 7dfea9d2\ d361089f\ 0a7a0247\ a184e1c7\ 0d417866\ e0fe0feb\ 0ff8f2f3\ f9176418\ f97d117e\ 624e2015\ df1662a8$
 $P_y = 004a3642\ 0572616c\ df7e606f\ ccadaecf\ c3b76dab\ 0eb1248d\ d03fbdfc\ 9cd3242c\ 4726be57\ 9855e812\ de7ec5c5\ 00b4576a\ 24628048\ b6a72d88\ 0062eed0\ dd34b109\ 6d3acbb6\ b01a4a97$

Polynomial Basis:

$Q_x = 01e263e6\ afad323f\ 934e50e4\ da0b015b\ 3f6727f4\ 27701cc3\ 0dcd1145\ c12e3c66\ 50ccd260\ 5cccd5a6a\ 609c5acd\ 3aed9e2d\ 32de8e64\ 80303414\ dc0907f0\ 21f8cef0\ cfb45700\ 56f8d686$
 $Q_y = 06c99cbb\ 0c686a6e\ d6b7015d\ e2cbe18a\ 3f623ae2\ c87ab4a3\ d6cd7b78\ b37f49cc\ 5e88de04\ b5668dad\ 2df3f34c\ 50b8c56a\ 3140d87f\ 81abb42e\ 919b3f8d\ 61743ba9\ 14bcb11b\ defda5cf$

Normal Basis:

$Q_x = 01ece446\ 40b698fe\ eb575fc0\ 65156c5f\ f94c277a\ 5335e1a2\ 28b65c22\ aff27777\ d159cf0ee\ c7f1270c\ c84bca33\ 8f34ab4d\ 6748f592\ bf322442\ e2ffeffe\ 9e5a321d\ cd6b4e75\ a269e745$
 $Q_y = 01cadada7\ 5647bba5\ 8c08b5e2\ 2b633e3a\ 5dd3b2c9\ 5db81f2d\ 220cba3d\ 7a38e692\ 072b3db2\ 6465b27a\ 2abd56b4\ 2291f982\ 3a902eb5\ 038d162a\ 7a578d37\ 8dd0c620\ 4f722521\ b8084d4c$

A.2 Test Moduli for the MS_DRBG (...)

Each modulus is of the form $n = pq$ with $p = 2p_1 + 1$, $q = 2q_1 + 1$, where p_1 and q_1 are $(\lg(n)/2 - 1)$ -bit primes.

A.2.1 The Test Modulus n of Size 2048 Bits

The hexadecimal value of the modulus n is:

```
c11a01f2 5daf396a a927157b af6f504f 78cba324 57b58c6b  
f7d851af 42385cc7 905b06f4 1f6d47ab 1b3a2c12 17d14d15  
070c9da5 24734ada 2fe17a95 e600ae9a 4f8b1a66 96661e40  
7d3043ec d1023126 5d8ea0d1 81cf23c6 dd3dec9e b3fce204  
5b9299bb cca63dee 435a2251 ad0765d4 9d29db2e f5aba161  
279aeb5f 6899fe48 7973e36c 1fb13086 d9231b6b 925a8495  
4ba0fbca fea844ea 77a9f852 f86915a4 e71bd0ba b9b269c3  
9a7a827a 41311ffa 4470140c 8b6509fe 5dbd39e3 ec816066  
2d036e13 0e07e233 06a39b18 db0e8efe 64418880 81ac3673  
2b4091f6 63690d03 3b486d74 371a20fc 3e214bce 7ed0e797  
5ea44453 cd161d32 e8185204 59896571
```

A.2.2 The Test Modulus n of Size 3072 Bits

The hexadecimal value of the modulus n is:

```
c6046ba6 8beaa061 c468a9a7 4da34d64 21398c73 020837c7  
d2a4042b dd9a7628 cab8022e 5bc4246f 75da8d26 03da8021  
41c5d112 835e6bdb 57ed799e 28d6fa49 c3d0f5b5 f9776c14  
0a901bf7 73ae3113 35d0470e da91b442 dbac621a cdd324e2  
a70244d7 cb155adc 4b77dd94 fafe069d 5b5cc494 86e9fe61  
c5081190 abb24f54 2d7d21e9 c90453c6 9ac63143 401d6b35  
e456ea2f 64ae76f9 2df80328 b48f7962 d5c9b779 b2078496  
7d374f02 06b8afbf 678d7f5f 36c3d84e c9e55c28 7ce5c668  
17ee05b4 1059168f b5c5e2a3 6bc2f6ce 3b43bd14 56eebdd5  
70ffe61e 5a7023a9 04d98f8a 96bfaf55 55a12f81 5561b401  
63f3a50e ale16a36 3f5cddd4 a1db275c 4fc2d650 d51f1e93  
f5fd7631 ca45914f f6fe62a0 be55b997 5f6566bb 47e76276  
f4e3b2eb 837bf0da 9d824687 042479a3 04147399 2d814a3a  
7be7bc3d 06992df6 6c1d7d06 f8c1410e 2bbb573a 0e278e7a  
daa600f3 2577030e 95b73dd9 96b65f98 4740a485 e27138bd  
d5f02522 09bcf005 6640a1b3 b1dd97ad 7c187e04 01ba817d
```

ANNEX B : (Normative) Conversion and Auxilliary Routines

B.1 Bitstring to an Integer

Input:

1. b_1, b_2, \dots, b_n The bitstring to be converted.

Output:

1. x The requested integer representation of the bitstring.

Process:

1. Let (b_1, b_2, \dots, b_n) be the bits of b from leftmost to rightmost.

$$x = \sum_{i=1}^n 2^{(n-i)} b_i .$$

3. Return x .

In this Standard, the binary length of an integer x is defined as the smallest integer n satisfying $x < 2^n$.

B.2 Integer to a Bitstring

Input:

1. x The non-negative to be converted.

Output:

1. b_1, b_2, \dots, b_n The bitstring representation of the integer x .

Process:

1. Let (b_1, b_2, \dots, b_n) represent the bitstring, where $b_1 = 0$ or 1 , and b_1 is the most significant bit, while b_n is the least significant bit.

2. For any integer n that satisfies $x < 2^n$, the bits b_i shall satisfy:

$$x = \sum_{i=1}^n 2^{(n-i)} b_i .$$

3. Return b_1, b_2, \dots, b_n .

In this Standard, the binary length of the integer x is defined as the smallest integer n that satisfies $x < 2^n$.

B.3 Integer to an Octet String

Input:

ANS X9.82, Part 3 - DRAFT - March 2005

1. A non-negative integer x , and the intended length n of the octet string satisfying
 $2^{8n} > x$.

Output:

1. An octet string O of length n octets.

Process:

1. Let O_1, O_2, \dots, O_n be the octets of O from leftmost to rightmost.
2. The octets of O **shall** satisfy:

$$x = \sum 2^{8(n-i)} O_i$$

for $i = 1$ to n .

3. Return O .

B.4 Octet String to an Integer

Input:

1. An octet string O of length n octets.

Output:

1. A non-negative integer x .

Process:

1. Let O_1, O_2, \dots, O_n be the octets of O from leftmost to rightmost.
2. x is defined as follows:

$$x = \sum 2^{8(n-i)} O_i$$

for $i = 1$ to n .

3. Return x .

Annex C: (Informative) Security Considerations

C.1 The Security of Hash Functions

[Add a discussion as to why it is OK to use SHA-1 to generate pseudorandom curves of greater than 80 bits of security. The security strength of a hash function for these generators is = the output block size. If there is no vulnerability to collision (e.g., when a hash function is used as an element in a well-designed RNG) and the function is not invertible, then the strength is = the ouput block size. However, when a hash function is used as an element in an application/cryptographic service where vulnerability to collisions is a consideration, then the strength = half the size of the output block.]]

C.2 Algorithm and Keysize Selection

This section provides guidance for the selection of appropriate algorithms and key sizes. It emphasizes the importance of acquiring cryptographic systems with appropriate algorithms and key sizes to provide adequate protection for 1) the expected lifetime of the system and 2) any data protected by that system during the expected lifetime of the data. Also included is the necessity for selecting appropriate random bit generators to support the cryptographic algorithms.

Cryptographic algorithms provide different levels (i.e., different “strengths”) of security, depending on the algorithm and the key size used. Two algorithms are considered to be of equivalent strength for the given key sizes (X and Y) if the amount of work needed to “break the algorithms” or determine the keys (with the given key sizes) is approximately the same using a given resource. The strength of an algorithm (sometimes called the work factor) for a given key size is traditionally described in terms of the amount of work it takes to try all keys for a symmetric algorithm with a key size of “ X ” that has no short cut attacks (i.e., the most efficient attack is to try all possible keys). In this case, the best attack is said to be the exhaustion attack. An algorithm that has a “ Y ” bit key, but whose strength is equivalent to an “ X ” bit key of such a symmetric algorithm is said to provide “ X ” bits of security” or to provide “ X -bits of strength”. An algorithm that provides X bits of strength would, on average, take $2^{X-1}T$ to attack, where T is the amount of time that is required to perform one encryption of a plaintext value and comparison of the result against the corresponding ciphertext value.

Determining the security strength of an algorithm can be nontrivial. For example, consider TDEA. TDEA uses three 56-bit keys (K_1 , K_2 and K_3). If each of these keys is independently generated, then this is called the three key option or three key TDEA (3TDEA). However, if K_1 and K_2 are independently generated, and K_3 is set equal to K_1 , then this is called the two key option or two key TDEA (2TDEA). One might expect that 3TDEA would provide $56 \times 3 = 168$ bits of strength. However, there is an attack on 3TDEA that reduces the strength to the work that would be involved in exhausting a 112-bit key. For 2TDEA, if exhaustion were the best attack, then the strength of 2TDEA would be $56 \times 2 = 112$ bits. This appears to be the case if the attacker has only a few matched

plain and cipher pairs. However, if the attacker can obtain approximately 2^{40} such pairs, then 2TDEA has strength that is comparable to an 80-bit algorithm (see [ASCX9.52], Annex B) and, therefore, is not appropriate for this Standard, since the lowest security strength provides 112 bits of security.

The comparable key sizes discussed in this section are based on assessments made as of the publication of this Standard. Advances in factoring algorithms, advances in general discrete logarithm attacks, elliptic curve discrete logarithm attacks and quantum computing may affect these assessments in the future. New or improved attacks or technologies may be developed that leave some of the current algorithms completely insecure. If quantum computing becomes a practical reality, the asymmetric techniques may no longer be secure. Periodic reviews will be performed to determine whether the stated comparable sizes need to be revised (e.g., the key sizes need to be increased) or the algorithms are no longer secure.

When selecting a block cipher cryptographic algorithm (e.g., AES or TDEA), the block size may also be a factor that should be considered, since the amount of security provided by several of the modes defined in [SP 800-38] is dependent on the block size⁵. More information on this issue is provided in [SP 800-38].

[Table 7 provides associated key sizes for the Approved algorithms and hash functions.

1. Column 1 indicates the security strength provided by the algorithms and key sizes in a particular row.
2. Column 2 provides the symmetric key algorithms that provide the indicated level of security (at a minimum), where TDEA is approved in [ASC X9.52], and AES is specified in [FIPS 197]. The table entry for TDEA requires the use of three distinct keys.
3. Column 3 provides the comparable security strengths for hash functions that are specified in FIPS180-2. The hash function entries assume that collision resistance is required (e.g., the application uses the hash function for digital signatures). For applications that are not concerned with collisions, the appropriate application standard will specify the appropriate hash functions for the security level. For this Standard, see Section 10.1.1 and Table 3.
4. Column 4 indicates the size of the parameters associated with the standards that use discrete logs and finite field arithmetic (DSA as defined in ASC X9.30 for digital signatures, and Diffie-Hellman (DH) and MQV key agreement as defined in [ANS X9.42], where L is the size of the modulus p , and N is the size of q . L is commonly considered to be the key size for the algorithm, although L is actually the key size of the public key, and N is the key size of the private key.

⁵ Suppose that the block size is b bits. The collision resistance of a MAC is limited by the size of the tag and collisions become probable after $2^{b/2}$ messages, if the full b bits are used as a tag. When using the Output Feedback mode of encryption, the maximum cycle length of the cipher can be at most 2^b blocks; the average cipher length is less than 2^b blocks. When using the Cipher Block Chaining mode, plaintext information is likely to begin to leak after $2^{b/2}$ blocks have been encrypted with the same key.

5. Column 5 defines the value for k (the size of the modulus n) for the RSA algorithm specified in ANS X9.31 for digital signatures, and specified in ANS X9.44 for key establishment. The value of k is commonly considered to be the key size.
6. Column 6 defines the value of f (the size of n , where n is the order of the base point G) for the discrete log algorithms using elliptic curve arithmetic that are specified for digital signatures in ANS X9.62, and for key establishment as specified in ANS X9.63. The value of f is commonly considered to be the key size.

Table 7: Equivalent strengths.

Bits of security	Symmetric key algs.	Hash functions	DSA, D-H, MQV	RSA	Elliptic Curves
112	3-key TDEA	SHA-224	$L = 2048$ $N = 224$	$k = 2048$	$f \geq 224$
128	AES-128	SHA-256	$L = 3072$ $N = 256$	$k = 3072$	$f \geq 256$
192	AES-192	SHA-384			$f \geq 384$
256	AES-256	SHA-512			

Comment [ebb7]: Page: 116
Strongly recommend removing this, as it is subject to change. NIST is now planning to put this information in SP 800-78.

C.3 Extracting Bits in the Dual_EC_DRBG (...)

C.3.1 Potential Bias Due to Modular Arithmetic for Curves Over F_p

For the mod p curves (i.e., a *Prime field curve*), there is a potential bias in the output due to the modular arithmetic. This behavior is succinctly explained in Part 1 of this Standard, and two approaches to correcting the bias are presented there. The Negligible Skew Method described in Section 14.2.2 of Part 1 is appropriate for the NIST curves, since all were selected to be over prime fields near a power of 2 in size. Each NIST prime has at least 32 leading 1's in its binary representation, and at least 16 of the leftmost (high-order) bits are discarded in each block produced. These two facts imply that there is a small fraction ($\leq 1/2^{32}$) of *outlen* outputs for which a bias to 0 may occur in one or more bits. This can only happen when the first 32 bits of an *x*-coordinate are all zero. As the leftmost 16 bits (at least) are discarded, an adversary can never be certain when a "biased" block has occurred. Thus, any bias due to the modular arithmetic may safely be ignored.

C.3.2 Adjusting for the missing bit(s) of entropy in the x coordinates.

In a truly random sequence, it should not be possible to predict any bits from previously observed bits. With the **Dual_EC_DRBG** (...), the full output block of bits produced by the algorithm is "missing" some entropy. Fortunately, by discarding some of the bits, those bits remaining can be made to have nearly "full strength", in the sense that the

entropy that they are missing is negligibly small.

To illustrate what can happen, suppose that a mod p curve with $m=256$ is selected, and that all 256 bits produced were output by the generator, i.e. that $outlen = 256$ also. Suppose also that 255 of these bits are published, and the 256-th bit is kept "secret". About $\frac{1}{2}$ the time, the unpublished bit could easily be determined from the other 255 bits. Similarly, if 254 of the bits are published, about $\frac{1}{4}$ of the time the other two bits could be predicted. This is a simple consequence of the fact that only about $1/2$ of all 2^m bitstrings of length m occur in the list of all x coordinates of curve points.

The situation is slightly worse with the binary curves, since each has a cofactor of 2 or 4. This means that only about $1/4$ or $1/8$, respectively, of the m -bitstrings occur as x coordinates. Thus, the NIST elliptic curves have m -bit outputs that are lacking 1,2 or 3 bits of entropy, when taken in their entirety.

The "abouts" in the preceding example can be made more precise, taking into account the difference between 2^m and p , and the actual number of points on the curve (which is always within $2 * p^{1/2}$ of p). For the NIST curves, these differences won't matter at the scale of the results, so they will be ignored. This allows the heuristics given here to work for any curve with "about" $(2^m)/f$ points, where $f = 1, 2$ or 4 is the curve's cofactor.

The basic assumption needed is that the approximately $(2^m)/(2f)$ x coordinates that do occur are "uniformly distributed": a randomly selected m -bit pattern has a probability $1/2f$ of being an x coordinate. The assumption allows a straightforward calculation,--albeit approximate--for the entropy in the rightmost (least significant) $m-d$ bits of

Dual_EC_DRBG output, with $d \ll m$.

The formula is $E = - \sum_{j=0}^{\infty} \{j=2^d\} [2^{\{m-d\}} \text{binomprob}(2^d, z, 2^d-j)] p_j \log_2\{p_j\}$.

The term in braces represents the approximate number of $(m-d)$ -bitstrings, which fall into one of $1+2^d$ categories as determined by the number of times j it occurs in an x coordinate; $z = (2f-1)/2f$ is the probability that any particular string occurs in an x coordinate; $p_j = (j*2f)/2^m$ is the probability that a member of the j -th category occurs. Note that the $j=0$ category contributes nothing to the entropy (randomness).

The values of E for d up to 16 are:

log2(f): 0	$d: 0$	entropy: 255.00000000	$m-d: 256$
log2(f): 0	$d: 1$	entropy: 254.50000000	$m-d: 255$
log2(f): 0	$d: 2$	entropy: 253.78063906	$m-d: 254$
log2(f): 0	$d: 3$	entropy: 252.90244224	$m-d: 253$
log2(f): 0	$d: 4$	entropy: 251.95336161	$m-d: 252$
log2(f): 0	$d: 5$	entropy: 250.97708960	$m-d: 251$
log2(f): 0	$d: 6$	entropy: 249.98863897	$m-d: 250$

ANS X9.82, Part 3 - DRAFT - March 2005

log2(f): 0 d: 7 entropy: 248.99434222 m-d: 249

log2(f): 0 d: 8 entropy: 247.99717670 m-d: 248

log2(f): 0 d: 9 entropy: 246.99858974 m-d: 247

log2(f): 0 d: 10 entropy: 245.99929521 m-d: 246

log2(f): 0 d: 11 entropy: 244.99964769 m-d: 245

log2(f): 0 d: 12 entropy: 243.99982387 m-d: 244

log2(f): 0 d: 13 entropy: 242.99991194 m-d: 243

log2(f): 0 d: 14 entropy: 241.99995597 m-d: 242

log2(f): 0 d: 15 entropy: 240.99997800 m-d: 241

log2(f): 0 d: 16 entropy: 239.99998900 m-d: 240

log2(f): 1 d: 0 entropy: 254.00000000 m-d: 256

log2(f): 1 d: 1 entropy: 253.75000000 m-d: 255

log2(f): 1 d: 2 entropy: 253.32398965 m-d: 254

log2(f): 1 d: 3 entropy: 252.68128674 m-d: 253

log2(f): 1 d: 4 entropy: 251.85475372 m-d: 252

log2(f): 1 d: 5 entropy: 250.93037696 m-d: 251

log2(f): 1 d: 6 entropy: 249.96572188 m-d: 250

log2(f): 1 d: 7 entropy: 248.98298045 m-d: 249

log2(f): 1 d: 8 entropy: 247.99151884 m-d: 248

log2(f): 1 d: 9 entropy: 246.99576643 m-d: 247

log2(f): 1 d: 10 entropy: 245.99788495 m-d: 246

log2(f): 1 d: 11 entropy: 244.99894291 m-d: 245

log2(f): 1 d: 12 entropy: 243.99947156 m-d: 244

log2(f): 1 d: 13 entropy: 242.99973581 m-d: 243

log2(f): 1 d: 14 entropy: 241.99986791 m-d: 242

log2(f): 1 d: 15 entropy: 240.99993397 m-d: 241

log2(f): 1 d: 16 entropy: 239.99996700 m-d: 240

log2(f): 2 d: 0 entropy: 253.00000000 m-d: 256

```

log2(f): 2 d: 1 entropy: 252.87500000 m-d: 255
log2(f): 2 d: 2 entropy: 252.64397615 m-d: 254
log2(f): 2 d: 3 entropy: 252.24578858 m-d: 253
log2(f): 2 d: 4 entropy: 251.63432894 m-d: 252
log2(f): 2 d: 5 entropy: 250.83126431 m-d: 251
log2(f): 2 d: 6 entropy: 249.91896704 m-d: 250
log2(f): 2 d: 7 entropy: 248.96005989 m-d: 249
log2(f): 2 d: 8 entropy: 247.98015668 m-d: 248
log2(f): 2 d: 9 entropy: 246.99010852 m-d: 247
log2(f): 2 d: 10 entropy: 245.99506164 m-d: 246
log2(f): 2 d: 11 entropy: 244.99753265 m-d: 245
log2(f): 2 d: 12 entropy: 243.99876678 m-d: 244
log2(f): 2 d: 13 entropy: 242.99938350 m-d: 243
log2(f): 2 d: 14 entropy: 241.99969178 m-d: 242
log2(f): 2 d: 15 entropy: 240.99984590 m-d: 241
log2(f): 2 d: 16 entropy: 239.99992298 m-d: 240

```

Observations:

- a) Each table starts where it should, at 1, 2 or 3 missing bits;
- b) The missing entropy rapidly decreases;
- c) Each doubling of the $\log_2(f)$ factor requires about 1 more bit to be discarded for the same level of entropy;
- d) For $\log_2(f) = 0$, i.e., the mod p curves, $d=13$ leaves 1 bit of information in every 10,000 ($m-13$)-bit outputs.

Based on these calculations, for the mod p curves, it is recommended that an implementation **shall** remove at least the **leftmost**, ie, most significant, 13 bits of every m -bit output, and that the **Dual_EC_DRBG** (...) be reseeded every 10,000 iterations. For the binary curves, either 14 or 15 of the leftmost bits **shall** be removed, as determined by the cofactor being 2 or 4, respectively. Using this value for d in the mod p curves insures that no bit has a bias from the modular reduction exceeding $1/2^{44}$

For ease of implementation, the value of d **should** be adjusted upward, if necessary, until the number of bits remaining, $m-d = \text{blocksize}$, is a multiple of 8. By this rule, the actual number of bits discarded from each block will range from 16 to 19.

ANNEX D: (Informative) Functional Requirements

[Should this annex be retained? Should it just address those requirements that are appropriate for DRBGs?]

D.1 General Functional Requirements

The following functional requirements apply to all random bit generators:

1. *The implementation shall be designed to allow validation testing; including documenting specific design assertions about how the RBG operates. This shall include mechanisms for testing all detectable error conditions.*

Implementation validation testing for DRBGs is discussed in Section 11.3.

2. *The RBG shall be designed with the intent of meeting the security properties in Part 1, Section 8. This is on a best effort basis, as aspects of some of these properties are not testable.*

Documentation requirement: There shall be design documentation that describes how the RBG is intended to meet all security properties, including protection from misbehavior.

The fulfillment of general RBG requirements is discussed in Part 4. Part 1, Section 8 includes discussions of backtracking and prediction resistance, RBG output properties and RBG operational properties. Part 3-specific requirements are discussed below. Documentation requirements for RBGs are listed in Section 11.2.

3. *The RBG shall support backtracking resistance.* [I still think this is a wasted statement, since implied by requirement 2.]

Backtracking resistance has been designed into each DRBG specified in Section 10.

Optional attributes for the functions in an RBG are as follows:

4. *The RBG may be capable of supporting prediction resistance.*

An optional prediction resistance capability is specified for the DRBG functions in Section 9.2 - 9.4 and is also discussed in Section 8.6.

D.2 Functional Requirements for Entropy Input

These requirements are addressed in Parts 2 and 4 of this Standard.

D.3 Functional Requirements for Other Inputs

No general function requirements are stated in Part 1 for other inputs. However, Part 3

requirements for other input are discussed in Section 7.2.3.

D.4 Functional Requirements for the Internal State

The requirements for the internal state of a RBG are:

1. *The internal state shall be protected in a manner that is consistent with the use and sensitivity of the output.*

The internal state **shall** be protected at least as well as the intended use of the pseudorandom output bits requested by the consuming application. (see Section 8.2.3).

2. *The internal state shall be functionally maintained properly across power failures, reboots, etc. or regain a secure condition before any output is generated (i.e., either the integrity of the internal state shall be assured, or the internal state shall be re-initialized with a new statistically unique value).*

This requirement is outside the scope of this Standard. Fulfilling this requirement may be addressed, for example, by implementing the DRBG in a FIPS 140-2 validated module. Further discussion of this requirement will be addressed in Part 4.

3. *The RBG shall satisfy the requirements for a particular security strength (from the set of [112, 128, 192, 256, or potentially unlimited]) in the internal state components.*

Documentation requirement: The security strength provided by the RBG shall be documented.

Sections 8.4, 9.2, 9.3 and the DRBG algorithms in Section 10 address the acquisition of sufficient entropy for the seed to satisfy a given security strength. Documentation requirements are listed in Section 11.2.

D.5 Functional Requirements for the Internal State Transition Function

The requirements for the internal state transition functions of an RBG are:

1. *The deterministic elements of internal state transition functions shall be verifiable via known-answer testing during installation and/or startup and/or initialization, and periodic health tests.*

A DRBG **shall** perform self-tests to ensure that the DRBG continues to function properly. Self tests are discussed in Sections 9.7 and 11.4.

2. *The internal state transition function shall, over time, depend on all the entropy carried by the internal state. That is, added entropy shall affect the internal state.*

This requirement is fulfilled by the design of the DRBGs specified in Section 10.

3. *The Internal State Transition Function shall resist observation and analysis via*

power consumption, timing, radiation emissions, or other side channels as appropriate, depending on the access by an observer who could be an adversary. What is appropriate (if anything) depends on the details of the implementation and shall be described by the implementation documentation.

Documentation requirement: This aspect of the design shall be documented.

This requirement is outside the scope of this Standard. Fulfilling this requirement may be addressed, for example, by implementing the DRBG in a FIPS 140-2 validated module. Part 4 will address this requirement further.

4. *It shall not be feasible (either intentionally or unintentionally) to cause the Internal State Transition Function to return to a prior state in normal operation (this excludes testing and authorized verification of the RBG output), except possibly by chance (depending on the specific design).*

This requirement is fulfilled by the design of the DRBGs specified in Section 10.

D.6 Functional Requirements for the Output Generation Function

The functional requirements for the output generation function are:

1. *The output generation function shall be deterministic (given all inputs) and shall allow known-answer testing when requested.*

The determinism of the output generation function is inherent in the DRBG algorithm designs of Section 10. Known answer testing is discussed in Sections 9.7, 11.3 and 11.4.

2. *The output shall be inhibited until the internal state obtains sufficient assessed entropy.*

Section 8.4 states that a DRBG **shall not** provide output until a seed is available. Sections 9.2 - 9.5 request entropy at appropriate times during the instantiate, reseed and generate functions.

3. *Once a particular internal state has been used for output, the internal state shall be changed before more output is produced. The OGF shall not reuse any bit from the subset of bits of the pool that were used to produce output. An ISTF shall either update the internal state between successive actions of the OGF, or the OGF shall select independent subsets of bits in the internal state without reusing any previously selected bits between updates of the internal state by the ISTF. In the latter case, this process shall update the internal state in order to select a different set of bits from the "pool" of bits from which output is to be derived.*

Documentation requirement: This aspect of the design shall be documented.

The specifications for the DRBG algorithms in Section 10 include an update of the internal state prior to returning the requested pseudorandom bits to the consuming application. Documentation requirements are listed in Section 11.2.

4. *Test output from a known answer test shall be separated from operational output (e.g., random output that is used for a cryptographic purpose).*

Section 11.4.1 states that all data output from the DRBG module **shall** be inhibited while operational tests are performed. The results from known-answer tests **shall not** be output as random bits during normal operation.

5. *The output generation function shall protect the internal state, so that analysis of RBG outputs does not reveal useful information (from the point of view of compromise) about the internal state that could be used to reveal information about other outputs.*

The DRBG algorithms specified in Section 10 have been designed to fulfill this requirement.

6. *The output generation function shall use information from the internal state that contains sufficient entropy to support the required security strength.*

Documentation requirement : This aspect of the design shall be documented.

Providing that the seed used to initialize the DRBG contains the appropriate amount of entropy for the required security strength, the output generation function in the DRBGs in this Standard have been designed to fulfill this requirement. Documentation requirements are listed in Section 11.2.

7. *The output generation function shall resist observation and analysis via power consumption, timing, radiation emissions, or other side channels as appropriate.*

Documentation requirement: This aspect of the design shall be documented.

This requirement is outside the scope of this Standard. Fulfilling this requirement may be addressed, for example, by implementing the DRBG in a FIPS 140-2 validated module. Part 4 will discuss this requirement further.

D.7 Functional Requirements for Support Functions

The functional requirements for support functions in Part 1 are:

1. *An RBG shall be designed to permit testing that will ensure that the generator continues to operate correctly. These tests shall be performed at start-up (after either initialization or re-initialization), upon request and may also be performed periodically or continuously.*

Section 11.4 specifies a requirement for operational (health) testing. A general method for operational testing is provided in Section 9.7.

2. *Output shall be inhibited during power-up, on-request and periodic testing until testing is complete and the result is acceptable. If the result is not acceptable, the RBG shall enter an error state.*

Section 11.4 specifies that operational testing **shall** be conducted during power-up,

ANS X9.82, Part 3 - DRAFT - March 2005

on demand and at periodic intervals; this section also specifies that output **shall** be inhibited during testing. Section 9.7 specifies operational tests.

3. *Output need not be inhibited during continuous testing unless an unacceptable result is encountered. When an unacceptable result is thus determined, output shall be inhibited, and the RBG shall enter an error state.*

Continuous testing is not specified for DRBGs.

4. *When an RBG fails a test, the RBG shall enter an error state and output an error indicator. The RBG shall not perform any operations while in the error state. The other parts of this Standard address error recovery in more detail, as appropriate.*

Section 11.4 specifies this requirement. Sections 9.7 and 9.8 discuss the error handling process.

5. *Any other support functions implemented shall be documented regarding their purpose and the principles used in their design.*

Documentation requirements are listed in Section 11.2.

ANNEX E: (Informative) DRBG Selection

E.1 Choosing a DRBG Algorithm

Comment [ebb8]: Page: 126
Some of this may need to be revised, based on
the content of Part 4.

Almost no system designer starts with the idea that he's going to generate good random bits. Instead, he typically starts with some goal that he wishes to accomplish, then decides on some cryptographic mechanisms such as digital signatures or block ciphers that can help him achieve that goal. Typically, as he begins to understand the requirements of those cryptographic mechanisms, he learns that he will also have to generate some random bits, and that this must be done with great care, or he may inadvertently weaken the cryptographic mechanisms that he has chosen to implement. At this point, there are two things that may guide the designer's choice of a DRBG:

- a. He may already have decided to include a block cipher, hash function, keyed hash function, etc., as part of his implementation. By choosing a DRBG based on one of these mechanisms, he can minimize the cost of adding that DRBG. In hardware, this translates to lower gate count, less power consumption, and less hardware that must be protected against probing and power analysis. In software, this translates to fewer lines of code to write, test, and validate.

For example, a designer of a module that does RSA signatures probably already has available some kind of hashing engine, so one of the hash-based DRBGs is a natural choice.

- b. He may already have decided to trust a block cipher, hash function, keyed hash function, etc., to have certain properties. By choosing a DRBG based on similar properties of these mechanisms, he can minimize the number of algorithms he has to trust.

For example, a designer of a module that provides encryption with AES can implement an AES-based DRBG. Since the DRBG is based for its security on the strength of AES, the module's security is not made dependent on any additional cryptographic primitives or assumptions.

The DRBGs specified in this standard have different performance characteristics, implementation issues, and security assumptions.

E.2 DRBGs Based on Hash Functions

Two DRBGs are based on any Approved hash function: **Hash_DRBG**, and **HMAC_DRBG**. A hash function is composed of an initial value, a padding mechanism and a compression function; the compression function itself may be expressed as **Compress** (I, X), where I is the initial value, and X is the compression function input. All of the cryptographic security of the hash function depends on the compression function,

and the compression is by far the most time-consuming operation within the hash function.

The hash-based DRBGs in this Standard allow for some tradeoffs between performance, security assumptions required for the security of the DRBGs, and ease of implementation.

E.2.1 Hash_DRBG

Hash_DRBG is closely related to the DRBG specified in FIPS-186-2, and can be seen as an updated version of that DRBG that can be used as a general-purpose DRBG. Although a formal analysis of this DRBG is not available, it is clear that the security of the DRBG depends on the security of **Hashgen**. Specifically, an attacker can get a large number of sequences of values:

Hash (V), **Hash** ($V+1$), **Hash** ($V+2$), ...

If the attacker can distinguish any of these sequences from a random sequence of values, then the DRBG can be broken.

E.2.1.1 Implementation Issues

This DRBG requires a hash function, some surrounding logic, and the ability to add numbers modulo $2^{seedlen}$, where $seedlen$ is the length of the seed. **Hash_DRBG** also uses **hash_df** internally when instantiating, reseeding, or processing additional input. Note that **hash_df** requires only access to a general-purpose hashing engine and the use of a 48-bit counter. The “critical state values” on which the **Hash_DRBG** depends for its security (V , C and *reseed_counter*) require $seedlen + outlen + 48$ bits of memory⁶.

E.2.1.2 Performance Properties

Each time that **Hash_DRBG** is called, a compression function computation is required for each $outlen$ bits of requested output (or portion thereof), where $outlen$ is the size of the hash function output block. For example, if $outlen = 160$, and 360 bits of pseudorandom data are requested, three compression function calls are made (two to produce the first 320 bits, and a third from which to select the remaining 40 bits. In addition, there is a certain amount of overhead to updating the state in order to achieve backtracking resistance; this requires one compression function call and some additions modulo $2^{seedlen}$, plus the update of *reseed_counter*. For the above example, a total of four compression function calls are required, three to generate the requested output bits, and one to update the state.

E.2.2 HMAC_DRBG

HMAC_DRBG is a DRBG whose security is based on the assumption that HMAC is a pseudorandom function. The security of **HMAC_DRBG** is based on an attacker getting sequences of up to 2^{35} bits, generated by the following steps:

temp = the Null string.

While (**len** (*temp*) < *requested_no_of_bits*):

⁶ V is $seedlen$ bits long, C is $outlen$ bits long (where $outlen$ is the length of the hash function output block), and *reseed_counter* is a maximum of 48 bits in length.

$V = \text{HMAC}(K, V)$.

$\text{temp} = \text{temp} \parallel V$.

The steps in the “While” statement iterate $\lceil \text{requested_no_of_bits}/\text{outlen} \rceil$ times. Intuitively, so long as V does not repeat, any algorithm that can distinguish this output sequence from an ideal random sequence can be used in a straightforward way to distinguish HMAC from a pseudorandom function.

Between these output sequences, both V and K are updated using the following steps (assuming no additional inputs):

$K = \text{HMAC}(K, (V \parallel 0x01)) = \text{Hash}(\text{opad}(K) \parallel \text{Hash}(\text{ipad}(K) \parallel (V \parallel 0x01)))$.

$V = \text{HMAC}(K, V) = \text{Hash}(\text{opad}(K) \parallel (\text{Hash}(\text{ipad}(K) \parallel V))$.

where:

K and V are outlen bits long,

$\text{opad}(K)$ is K exclusive-ored with $(\text{inlen}/8)$ bytes of 0x5c, for a total of inlen bits,

$\text{ipad}(K)$ is K exclusive-ored with $(\text{inlen}/8)$ bytes of 0x36, for a total of inlen bits,

outlen is the length of the hash function output block, and

inlen is the length of the hash function input block.

E.2.2.1 Implementation Properties

The only thing required to implement this DRBG is access to a hashing engine. However, the performance of the implementation will improve enormously (by about a factor of two!) with either a dedicated **HMAC** engine, or direct access to the hash function's underlying compression function. The “critical state values” on which **HMAC_DRBG** depends for its security (K and V) take up $2 * \text{outlen}$ bits in the most compact form, but for reasonable performance, $3 * \text{outlen}$ bits are required in order to precompute padded values.

E.2.2.2 Performance Properties

HMAC_DRBG is about a factor of two slower than **Hash_DRBG** for long bitstrings produced by a single request. That is, each outlen -bit piece of the requested pseudorandom output requires two compression function calls to perform the **HMAC** computation. Each output request also incurs another six compression function calls to update the state.

Note that an implementation that has access only to a high-level hashing engine loses another factor of two in performance; if the performance of the DRBG is important, **HMAC_DRBG** requires either a dedicated **HMAC** engine or access to the compression function that underlies the hash function. However, if performance is not an important issue, the DRBG can be implemented using nothing but a high-level hashing engine.

E.2.3 Summary and Comparison of Hash-Based DRBGs

E.2.3.1 Security

It is interesting to contrast the two ways that the hash function is used in these DRBGs:

Hash DRBG:

Hash (V), Hash (V+1), Hash (V+2)...

The only unknown input into the compression function used by the hash function is this sequence of secret values, $V+i$. Since the initial value of the hash function is publicly known, the adversary is given full knowledge of all but $seedlen$ bits of input into the compression function, and knowledge of the close relationship between these inputs, as well.

HMAC DRBG:

$V_1 = \text{HMAC}(K, V_0) = \text{Hash}(\text{opad}(K) \parallel (\text{Hash}(\text{ipad}(K) \parallel V_0)))$.

$V_2 = \text{HMAC}(K, V_1) = \text{Hash}(\text{opad}(K) \parallel (\text{Hash}(\text{ipad}(K) \parallel V_1)))$.

$V_3 = \text{HMAC}(K, V_2) = \text{Hash}(\text{opad}(K) \parallel (\text{Hash}(\text{ipad}(K) \parallel V_2)))$.

etc

as specified in Annex E.2.2.

The adversary knows many specific bits of the input to the final compression function whose output he sees; for SHA-256, the compression function takes a total of 768 bits of input, and the adversary knows 256 of those bits⁷. (This is worse for SHA-1 and SHA-384.) On the other hand, the adversary doesn't even know the exclusive-or relationships for $outlen$ bits of the message input. In the case of SHA-256, this means that 256 bits are unknown.

It is clear that Hash DRBG makes stronger assumptions on the strength of the compression function, although they are not precisely comparable. Specifically, HMAC DRBG allows an adversary to precisely know many bits of the input to the compression functions, but not to know complete exclusive-or or additive relationships between these bits of input.

⁷ The innermost hash function provides $outlen$ bits of input after its two compression function calls on $\text{ipad}(K)$ and V . The outermost hash function also requires two compression functions: the first operates on $\text{opad}(K)$ and produces $outlen$ bits that are used as the chaining value for the final compression function on the result from the innermost hash function concatenated with the hash function padding. Therefore, the input to the final compression function is the length of the chaining value ($outlen$ bits) + the length of the output from the innermost hash function ($outlen$ bits) + the length of the padding ($inlen - outlen$ bits). In the case of SHA-256, where $inlen = 512$, and $outlen = 256$, the length of the input to the last compression function is 768 bits, of which only the padding bits are known (256 bits).

E.2.3.2 Performance / Implementation Tradeoffs

The following performance and implementation tradeoffs should be considered when selecting a hash-based DRBG with regard to the overhead associated with requesting pseudorandom bits, the cost of actually generating $outlen$ bits (not including the overhead), and the memory required for the critical state values for each DRBG. The overhead is, essentially, the cost of updating the state prior to the next request for pseudorandom bits. The cost of generating each $outlen$ block of bits of output should be multiplied by the number of $outlen$ -bit blocks of output required in order to obtain the true cost of pseudorandom bit generation. Both the overhead and generation costs assume that prediction resistance and reseeding are not required, and that additional input is not provided for the request; if this is not the case, the costs are increased accordingly. Note that the memory requirements do not take into account other information in the state that is required for a given DRBG.

Hash DRBG:

Request overhead: one compression function and several additions mod $2^{seedlen}$.

Cost for $outlen$ bits of pseudorandom output: one compression function.

Memory required for the critical state values V , C and reseed counter: $inlen + outlen + 32$ bits.

HMAC DRBG (with access to the hash function's compression function):

Request overhead: six compression functions⁸.

Cost for $outlen$ bits of pseudorandom output: two compression functions.

Memory required for the critical state values K and V : $3 * outlen$ bits when precomputation is used.

HMAC DRBG (hash engine access only):

Request overhead: eight compression function calls⁹.

Cost for $outlen$ bits of pseudorandom output: four compression functions¹⁰.

Memory required for the critical state values K and V : $2 * outlen$ bits, since precomputation is unavailable.

For these DRBGs, additional inputs provided during pseudorandom bit generation add considerably to the request overhead. Instantiation and reseeding are somewhat more expensive than pseudorandom output generation; however, these relatively rare operations can afford to be somewhat more expensive to minimize the chances of a successful attack.

⁸ Two compression functions for each HMAC computation, and two compression functions for precomputation.

⁹ There are two HMAC computations, each requiring two hash function calls. Each hash computation requires two compression function calls.

¹⁰ The single HMAC computation requires four compression functions as explained in the previous footnote.

E.3 DRBGs Based on Block Ciphers

E.3.1 The Two Constructions: CTR and OFB

This standard describes two classes of DRBGs based on block ciphers: One class uses the block cipher in OFB-mode, the other class uses the CTR-mode. There are no practical security differences between these two DRBGs: CTR mode guarantees that short cycles cannot occur in a single output request, while OFB-mode guarantees that short cycles will have an extremely low probability. OFB-mode makes slightly less demanding assumptions on the block cipher, but the security of both DRBGs relates in a very simple and clean way to the security of the block cipher in its intended applications. This is a fundamental difference between these DRBGs and the DRBGs based on hash functions, where the DRBG's security is ultimately based on pseudorandomness properties that do not form a normal part of the requirements for hash functions. An attack on any of the hash-based DRBGs does not necessarily represent a weakness in the hash function; however, for these block cipher-based constructions, a weakness in the DRBG is directly related to a weakness in the block cipher.

Specifically, suppose that there is an algorithm for distinguishing the outputs of either DRBG from random with some advantage. If that algorithm exists, it can be used to build a new algorithm for distinguishing the block cipher from a random permutation, with the same time and memory requirements and advantage.

Because there is no practical security difference between the two classes of block-cipher based DRBGs, the choice between the two constructions is entirely a matter of implementation convenience and performance. An implementation that uses a block cipher in OFB, CBC, or full-block CFB mode can easily be used to implement the OFB-based DRBG construction; an implementation that already supports counter mode can reuse that hardware or software to implement the counter-mode DRBG. In terms of performance, the CTR-mode construction is more amenable to pipelining and parallelism, while the OFB-mode construction seems to require slightly less supporting hardware.

E.3.2 Choosing a Block Cipher

While security is not an issue in choosing between the two DRBG constructions, the choice of the block cipher algorithm to be used is more of an issue. At present, only TDEA and AES are approved block cipher algorithms. However, the two block cipher DRBG constructions will work for any block cipher with a block length ≥ 64 and key length ≥ 112 . TDEA's 64-bit block imposes some fundamental limits on the security of these constructions, though these limits don't appear to lead to practical security issues for most applications.

Consider a sequence of the maximum permitted number of generate requests, each producing the maximum number of DRBG outputs from each generate call. Assuming that the block cipher behaves like a pseudorandom permutation family, the probability of distinguishing the full sequence of output bytes is:

1. For AES-128, there are a maximum of 2^{28} blocks (i.e., 2^{32} bytes = 2^{35} bits) generated per Generate (...) request. 2^{32} total Generate (...) requests allowed. 2^{128} possible keys, and 2^{128} possible starting blocks.
 - a. The probability of an internal collision in a single Generate (...) request is never higher than about 2^{-96} , and so the probability of an internal collision in any given Generate (...) request is never higher than about 2^{-64} . (This applies only to the OFB-mode, but a collision of this kind would result in a very easy distinguisher.)
 - b. The expected probability of an internal collision in a sequence of 2^{28} random 128-bit blocks is about 2^{-74} . Thus, the probability of seeing an internal collision in any of the Generate (...) sequences is about 2^{-42} . This probability is low enough that it does not provide an efficient way to distinguish between DRBG outputs and ideal random outputs.
 - c. The probability of a key colliding between any two Generate (...) requests in the sequence of 2^{32} such requests is never larger than about 2^{-65} . This is also negligible. (For AES-192 and AES-256, this probability is even smaller.)
2. For three-key TDEA with 168-bit keys and 64-bit blocks, things are a bit different. There are 2^{16} Generate (...) requests allowed, and a maximum of 2^{13} blocks (i.e., 2^{16} bytes = 2^{19} bits) generated per Generate (...) request. (Note that this breaks the more general model in this document of assuming 2^{64} innocent operations.) In this case:
 - a. The probability of an internal collision is never higher than about 2^{-51} per Generate (...) request, and with only 2^{16} such requests allowed, the probability of ever seeing such an internal collision in a sequence of requests is never more than about 2^{-35} . (Note that if more requests are allowed, as required by the 2^{64} bound assumed elsewhere in the document, there would be an unacceptably high probability of this event happening at least once.)
 - b. The expected probability of an internal collision in a sequence of 2^{13} 64-bit blocks is about 2^{-38} . Thus, the probability of ever seeing an internal collision in 2^{16} output sequences is still an acceptably low 2^{-22} . (Note that if more Generate (...) requests are allowed, there would be an unacceptably high probability of this happening, leading to an efficient distinguisher between this DRBG's outputs and ideal random outputs.)
 - c. The probability of a key colliding between any two of the 2^{16} Generate (...)

requests is about 2^{136} , which is negligible.

To summarize: block size matters much more than the choice of DRBG construction that is used. The limits on the numbers of **Generate** (...) requests and the number of output bits per request require frequent reseeding of the DRBG. Furthermore, the limits guarantee that even with reseeding, an adversary that is given a really long sequence of DRBG outputs from several reseedings cannot distinguish that output sequence from random reliably. The block cipher DRBGs used with TDEA are suitable for low-throughput applications, but not for applications requiring really large numbers of DRBG outputs. For concreteness, if an application is going to require more than 2^{32} output bytes (2^{35} bits) in its lifetime, that application should not use a block cipher DRBG with TDEA or any other 64-bit block cipher.

E.3.3 Conditioned Entropy Sources and the Derivation Function

[Some or all of this section probably belongs in Part 4]

The block cipher DRBGs are defined to be used in one of two ways for initializing the DRBG state during instantiation and reseeding: Either with freeform input strings containing some specified amount of entropy, or with full-entropy strings of precisely specified lengths. The freeform strings will require the use of a derivation function, whereas the use of full-entropy strings will not. The block cipher derivation function uses the block cipher algorithm to compute several parallel CBC-MACs on the input string under a fixed key and using different IVs, uses the result to produce a key and starting block, and runs the block cipher in OFB-mode to generate outputs from the derivation function. An implementation must choose whether to provide full entropy, or to support the derivation function. This is a high-level system design decision; it affects the kinds of entropy sources that may be used, the gate count or code size of the implementation, and the interface that applications will have to the DRBG. On one extreme, a very low gate count design may use hardware entropy sources that are easily conditioned, such as a bank of ring oscillators that are exclusive-ored together, rather than to support a lot of complicated processing on input strings. On the other extreme, a general-purpose DRBG implementation may need the ability to process freeform input strings as personalization strings and additional inputs; in this case, the block cipher derivation function must be implemented.

E.4 DRBGs Based on Hard Problems

The **Dual_EC_DRBG** and **MS_DRBG** base their security on a "hard" number-theoretic problem. For the types of curves used in the **Dual_EC_DRBG**, the Elliptic Curve Discrete Logarithm Problem has no known attacks that are better than the "meet-in-the-middle" attacks, with a work factor of $\sqrt{2^m}$. In the case of **MS_DRBG**, which is based loosely on the RSA problem, the work factor of the best algorithm is more complex to state, but well-established.

These algorithms are decidedly less efficient to implement than some of the others. However, in those cases where security is the utmost concern, as in SSL or IKE exchanges,

the additional complexity is not usually an issue. Except for dedicated servers, time spent on the exchanges is just a small portion of the computational load; overall, there is no impact on throughput by using a number-theoretic algorithm. As for SSL or IPSEC servers, more and more of these servers are getting hardware support for cryptographic primitives like modular exponentiation and elliptic curve arithmetic for the protocols themselves. Thus, it makes sense to utilize those same primitives (in hardware or software) for the sake of high-security random numbers.

E.4.1 Implementation Considerations

E.4.1.1 Dual_EC_DRBG

Random bits are produced in blocks of bits representing the x -coordinates on an elliptic curve.

Because of the various security levels allowed by this Standard there are multiple curves available, with differing block sizes. The size is always a multiple of 8, about 16 bits less than a curve's underlying field size. Blocks are concatenated and then truncated, if necessary, to fulfill a request for any number of bits up to a maximum per call of 10,000 times the block length. The smallest blocksize is 216, meaning that at least 2M bits can be requested on each call.)

An important detail concerning the Dual_EC_DRBG is that every call for random bits, whether it be for 2 million bits or a single bit, requires that at least one full block of bits be produced; no unused bits are saved internally from the previous call. Each block produced requires two point multiplications on an elliptic curve—a fair amount of computation. Applications such as IKE and SSL are encouraged to aggregate all their needs for random bits into a single call to Dual_EC_DRBG, and then parcel out the bits as required during the protocol exchange. A C structure, for example, is an ideal vehicle for this.

To avoid unnecessarily complex implementations, it should be noted that *every* curve in the Standard need not be available to an application. For instance, one may choose to do arithmetic only over the prime order fields in a software application, or perhaps a particular binary curve in a hardware application. To improve efficiency, there has been much research done on the implementation of elliptic curve arithmetic; descriptions and source code are available in the open literature.

As a final comment on the implementation of the Dual_EC_DRBG, note that having fixed base points offers a distinct advantage for optimization. Tables can be precomputed that allow nP to be attained as a series of point additions, resulting in an 8 to 10-fold speedup, or more, if space permits.

**Comment [ebb9]: Page: 134
Doesn't this violate our guidance somewhere ?**

E.4.1.2. Micali-Schnorr

Micali-Schnorr was designed to be a more efficient version of the predecessor algorithm, the Blum-Blum-Shub (BBS) DRBG. BBS uses the recursion $x_i = x_{i-1}^2 \bmod n$ to generate its state sequence, producing a single pseudorandom bit as the least significant bit of x_i . Later, it was shown that $O(\ln(\ln n))$ bits could be taken on each iteration, but this is still a

ANS X9.82, Part 3 - DRAFT - March 2005

very small percentage of those produced. The MS_DRBG allows a much larger percentage of n bits to be used on each iteration, and has an additional advantage in that no output bits are used to propagate the sequence. It does, however, rely on a stronger assumption for its security than the intractability of integer factorization.

As ANS X9.82 standard evolved, committee members argued for restricting the number of bits generated on each exponentiation to $O(\ln(\ln n))$ hard bits, as is done in BBS. The result is that the efficiency argument for choosing MS over BBS doesn't apply. Nonetheless, a user does have more options in the choice of parameters.

Micali_Schnorr offers an alternative to Dual_EC_DRBG in the class of algorithms based on a hard problem from number theory, and presents an advantage in its simplicity. All that's required for implementation is a routine that computes $x^e \bmod n$; this can be readily found in commercial and open source toolkits.

ANNEX F: (Informative) Example Pseudocode for Each DRBG

F.1 Preliminaries

The internal states in these examples are considered to be an array of states, identified by *state_handle*. A particular state is addressed as *internal_state(state_handle)*, where the value of *state_handle* begins at 0 and ends at *n*-1, and *n* is the number of internal states provided by an implementation. A particular element in the internal state is addressed by *internal_state(state_handle).element*.

The pseudocode in this annex does not include the necessary conversions (e.g., integer to bitstring) for an implementation. When conversions are required, they must be accomplished as specified in annex B.

The following routine is defined for these pseudocode examples:

Find_state_space (): A function that finds an unused internal state. The function returns a *status* (either “Success” or a message indicating that an unused internal state is not available) and, if *status* = “Success”, a *state_handle* that points to an available *internal_state* in the array of internal states. If *status* ≠ “Success”, an invalid *state_handle* is returned.

F.2 Hash_DRBG Example

F.2.1 Discussion

This example of **Hash_DRBG** uses the SHA-1 hash function, and prediction resistance is supported in the example. Both a personalization string and additional input are allowed. A 32-bit incrementing counter is used as the nonce for instantiation (*instantiation_nonce*); the nonce is initialized when the DRBG is installed (e.g., by a call to the clock or by setting it to a fixed value) and is incremented for each instantiation.

A total of 10 internal states are provided (i.e., 10 instantiations may be handled simultaneously).

For this implementation, the functions and algorithms are “inline”, i.e., the algorithms are not called as separate routines from the function envelopes.

The internal state contains values for *V*, *C*, *reseed_counter*, *security_strength* and *prediction_resistance_flag*, where *V* and *C* are bitstrings, and *reseed_counter*, *security_strength* and the *prediction_resistance_flag* are integers. A requested prediction resistance capability is indicated when *prediction_resistance_flag* = 1. Note: an empty internal state is represented as {Null, Null, 0, 0, 0}.

In accordance with Table 3 in Section 10.1.1, the 112 and 128 bit security strengths may be supported. Using SHA-1, the following definitions are applicable for the instantiate, generate and reseed functions and algorithms:

1. $\text{highest_supported_security_strength} = 128$.
2. Output block length (outlen) = 160.
3. Required minimum entropy for instantiation and reseed = security_strength .
4. Minimum entropy input length ($\text{min_entropy_input_length}$) = security_strength .
5. Seed length (seedlen) = 440.
6. Maximum number of bits per request ($\text{max_number_of_bits_per_request}$) = 5000 bits.
7. Reseed interval (reseed_interval) = 100,000 requests.
8. Maximum length of the personalization string ($\text{max_personalization_string_length}$) = 500 bits.
9. Maximum length of additional_input ($\text{max_additional_input_string_length}$) = 500 bits.
10. Maximum length of entropy input ($\text{max_entropy_input_length}$) = 1000.

F.2.2 Instantiation of Hash_DRBG

This implementation will return a text message and an invalid state handle (-1) when an error is encountered. Note that the value of $\text{instantiation_nonce}$ is an internal value that is always available to the instantiate function.

Note that this implementation does not check the $\text{prediction_resistance_flag}$, since the implementation can handle prediction resistance. However, if an application actually wants prediction resistance, the implementation expects that $\text{prediction_resistance_flag} = 1$ during instantiation; this will be used in the generate function in Annex F.2.4.

Instantiate_Hash_DRBG (...):

Input: integer ($\text{requested_instantiation_security_strength}$, $\text{prediction_resistance_flag}$), bitstring $\text{personalization_string}$.

Output: string status , integer state_handle .

Process:

Comment: Check the input parameters.

1. If ($\text{requested_instantiation_security_strength} > 128$), then **Return** ("Invalid $\text{requested_instantiation_security_strength}$ ", -1).
2. If ($\text{len}(\text{personalization_string}) > 500$), then **Return** ("Personalization_string too long", -1).

Comment: Set the security_strength to one of the valid security strengths.

3. If (*requested_instantiation_security_strength* ≤ 112), then *security_strength* = 112
 Else *security_strength* = 128.
 Comment: Get the *entropy_input*.
4. (*status, entropy_input*) = **Get_entropy** (*security_strength, security_strength, 1000*).
 5. If (*status* ≠ “Success”), then **Return** (“Failure indication returned by the *entropy_input* source.” || *status*, -1).
 Comment: Increment the nonce; actual coding must ensure that it wraps when it’s storage limit is reached.
6. *instantiation_nonce* = *instantiation_nonce* + 1.
 Comment: The instantiate algorithm is provided in steps 7-11.
7. *seed_material* = *entropy_input* || *instantiation_nonce* || *personalization_string*.
8. *seed* = **Hash_df** (*seed_material, 440*).
9. *V* = *seed*.
10. *C* = **Hash_df** ((0x00 || *V*), 440).
11. *reseed_counter* = 1.
 Comment: Find an unused internal state and save the initial values.
12. (*status, state_handle*) = **Find_state_space** ().
13. If (*status* ≠ “Success”), then **Return** (*status, -1*).
14. *internal_state* (*state_handle*) = {*V, C, reseed_counter, security_strength, prediction_resistance_flag*}.
15. **Return** (“Success”, *state_handle*).

F.2.3 Reseeding a Hash_DRBG Instantiation

The implementation is designed to return a text message as the *status* when an error is encountered.

Reseed_Hash_DRBG_Instantiation (...):

Input: integer *state_handle*, bitstring *additional_input*.

Output: string *status*.

Process:

- Comment: Check the validity of the *state_handle*.
1. If (*state_handle* > 9) or (*internal_state(state_handle)* = {Null, Null, 0, 0, 0}), then **Return** (“State not available for the *state_handle*”).

Comment: Get the internal state values needed to determine the new internal state.
 2. Get the appropriate *internal_state* values, e.g., *V* = *internal_state(state_handle).V*, *security_strength* = *internal_state(state_handle).security_strength*.

Check the length of the *additional_input*.
 3. If (*len (additional_input)* > 500), then **Return** (“*Additional_input* too long”).

Comment: Get the *entropy_input*.
 4. (*status, entropy_input*) = **Get_entropy** (*security_strength, security_strength, 1000*).

Comment: The reseed algorithm is provided in steps 7-11.
 5. If (*status* ≠ “Success”), then **Return** (“Failure indication returned by the *entropy_input* source.” || *status*).

Comment: Update the *working_state* portion of the internal state.
 6. *seed_material* = 0x01 || *V* || *entropy_input* || *additional_input*.
 7. *seed* = **Hash_df** (*seed_material*, 440).
 8. *V* = *seed*.
 9. *C* = **Hash_df** ((0x00 || *V*), 440).
 10. *reseed_counter* = 1.

Comment: Update the appropriate *state* values.
 - 11.1 *internal_state(state_handle).V* = *V*.
 - 11.2 *internal_state(state_handle).C* = *C*.
 - 11.3 *internal_state(state_handle.reseed_counter) = reseed_counter*.
 12. **Return** (“Success”).

F.2.4 Generating Pseudorandom Bits Using Hash_DRBG

The implementation returns a *Null* string as the pseudorandom bits if an error has been

detected. Prediction resistance is requested when *prediction_resistance_request* = 1.

In this implementation, prediction resistance is requested by supplying *prediction_resistance_request* = 1 when the **Hash_DRBG** function is invoked.

Hash_DRBG (...):

Input: integer (*state_handle*, *requested_no_of_bits*, *requested_security_strength*,
prediction_resistance_request), bitstring *additional_input*.

Output: string *status*, bitstring *pseudorandom_bits*.

Process:

Comment: Check the validity of the
state_handle.

1. If ((*state_handle* > 9) or (*state* (*state_handle*) = {Null, Null, 0, 0, 0})), then
Return (“State not available for the *state_handle*”, Null).

Comment: Get the internal state values.

2. $V = \text{internal_state}(\text{state_handle}).V$, $C = \text{internal_state}(\text{state_handle}).C$,
 $\text{reseed_counter} = \text{internal_state}(\text{state_handle}).\text{reseed_counter}$,
 $\text{security_strength} = \text{internal_state}(\text{state_handle}).\text{security_strength}$,
 $\text{prediction_resistance_flag} = \text{internal_state}(\text{state_handle}).\text{prediction_resistance_flag}$.

Comment: Check the validity of the other
input parameters.

3. If (*requested_no_of_bits* > 5000) then **Return** (“Too many bits requested”, Null).
4. If (*requested_security_strength* > *security_strength*), then **Return** (“Invalid
requested_security_strength”, Null).
5. If (*len* (*additional_input*) > 500), then **Return** (“*Additional_input* too long”, Null).
6. If ((*prediction_resistance_request* = 1) and (*prediction_resistance_flag* ≠ 1)),
then **Return** (“Prediction resistance capability not instantiated”, Null).

Comment: Reseed if necessary. Note that
since the instantiate algorithm is inline with
the functions, this step has been written as a
combination of steps 6 and 7 of Section 9.4
and step 1 of the generate algorithm in
Section 10.1.2.2.4. Because of this combined
step, step 11.4 of Section 7.4 is not required.

7. If ((*reseed_counter* > 100,000) OR (*prediction_resistance_request* = 1)), then

- 7.1 $status = \text{Reseed_Hash_DRBG_Instantiation}(\text{state_handle}, \text{additional_input})$.
 - 7.2 If ($status \neq \text{"Success"}$), then **Return** ($status, Null$).

Comment: Get the new internal state values.
 - 7.3 $V = \text{internal_state}(\text{state_handle}).V, C = \text{internal_state}(\text{state_handle}).C, \text{reseed_counter} = \text{internal_state}(\text{state_handle}).\text{reseed_counter}, \text{security_strength} = \text{internal_state}(\text{state_handle}).\text{security_strength}, \text{prediction_resistance_flag} = \text{internal_state}(\text{state_handle}).\text{prediction_resistance_flag}$.
 - 7.4 $\text{additional_input} = Null$.

Comment: Steps 8-16 provide the rest of the generate algorithm. Note that in this implementation, the **Hashgen** routine is also inline as steps 9-13.
 8. If ($\text{additional_input} \neq Null$), then do
 - 7.1 $w = \text{Hash}(0x02 \parallel V \parallel \text{additional_input})$.
 - 7.2 $V = (V + w) \bmod 2^{440}$.
 9. $m = \left\lceil \frac{\text{requested_no_of_bits}}{\text{outlen}} \right\rceil$.
 10. $\text{data} = V$.
 11. $W =$ the Null string.
 12. For $i = 1$ to m
 - 12.1 $w_i = \text{Hash}(\text{data})$.
 - 12.2 $W = W \parallel w_i$.
 - 12.3 $\text{data} = (\text{data} + 1) \bmod 2^{\text{seedlen}}$.
 13. $\text{pseudorandom_bits} =$ Leftmost ($\text{requested_no_of_bits}$) bits of W .
 14. $H = \text{Hash}(0x03 \parallel V)$.
 15. $V = (V + H + C + \text{reseed_counter}) \bmod 2^{440}$.
 16. $\text{reseed_counter} = \text{reseed_counter} + 1$.
- Comments: Update the *working_state*.
13. Update the changed values in the *state*.
 - 13.1 $\text{internal_state}(\text{state_handle}).V = V$.

13.2 *internal_state(state_handle).reseed_counter = reseed_counter.*

14. **Return** (“Success”, *pseudorandom_bits*).

F.3 HMAC_DRBG Example

F.3.1 Discussion

This example of HMAC_DRBG uses the SHA-256 hash function. The reseed and, thus, the prediction resistance is not provided. The nonce for instantiation consists of a random value with 64-bits of entropy; the nonce is obtained by increasing the call for entropy bits via the **Get_entropy** call by 64 bits (i.e., by adding 64 bits to the *security_strength* value).

A personalization string is allowed, but additional input is not. A total of 3 internal states are provided. For this implementation, the functions and algorithms are written as separate routines.

The internal state contains the values for *V*, *Key*, *reseed_counter*, and *security_strength*, where *V* and *C* are bitstrings, and *reseed_counter* and *security_strength* are integers.

In accordance with Table 3 in Section 10.1.1, security strengths of 112, 128, 192 and 256 may supported. Using SHA-256, the following definitions are applicable for the instantiate and generate functions and algorithms:

1. *highest_supported_security_strength* = 256.
2. Output block (*outlen*) = 256.
3. Required minimum entropy for instantiation = *security_strength* + 64 (this includes the entropy required for the nonce).
4. Minimum entropy input length (*min_entropy_input_length*) = *security_strength* + 64 (this includes the minimum length for the nonce).
5. Seed length (*seedlen*) = 440.
6. Maximum number of bits per request (*max_number_of_bits_per_request*) = 7500 bits.
7. Reseed_interval (*reseed_interval*) = 10,000 requests.
8. Maximum length of the personalization string (*max_personalization_string_length*) = 100.
9. Maximum length of the entropy input (*max_entropy_input_length*) = 1000.

F.3.2 Instantiation of HMAC_DRBG

This implementation will return a text message and an invalid state handle (-1) when an error is encountered.

Instantiate_HMAC_DRBG (...):

Input: integer (*requested_instantiation_security_strength*), bitstring

personalization_string.

Output: string *status*, integer *state_handle*.

Process:

Check the validity of the input parameters.

1. If (*requested_instantiation_security_strength* > 256), then **Return** (“Invalid *requested_instantiation_security_strength*”, -1).
2. If (**len** (*personalization_string*)>100), then **Return** (“*Personalization_string* too long”, -1)

Comment: Set the *security_strength* to one of the valid security strengths.

3. If (*requested_security_strength* ≤ 112), then *security_strength* = 112
Else (*requested_security_strength* ≤ 128), then *security_strength* = 128
Else (*requested_security_strength* ≤ 192), then *security_strength* = 192
Else *security_strength* = 256.

Comment: Get the *entropy_input* and the *nonce*.

4. *min_entropy* = *security_strength* + 64.
5. (*status, entropy_input*) = **Get_entropy** (*min_entropy, min_entropy, 1000*).
6. If (*status* ≠ “Success”), then **Return** (“Failure indication returned by the entropy source” || *status*, -1).

Comment: Invoke the instantiate algorithm.
Note that the *entropy_input* contains the *nonce*.

7. (*V, Key, reseed_counter*) = **Instantiate_algorithm** (*entropy_input, personalization_string*).
Comment: Find an unused internal state and save the initial values.
8. (*status, state_handle*) = **Find_state_space** ().
9. If (*status* ≠ “Success”), then **Return** (“No available state space” || *status*, -1).
10. *internal_state (state_handle)* = {*V, Key, reseed_counter, security_strength*}.
11. Return (“Success” and *state_handle*).

Instantiate_algorithm (...):

Input: bitstring (*entropy_input, personalization_string*).

Output: bitstring (V , Key), integer $reseed_counter$.

Process:

1. $seed_material = entropy_input \parallel personalization_string$.
2. Set Key to $outlen$ bits of zeros.
3. Set V to $outlen/8$ bytes of 0x01.
4. $(Key, V) = \text{Update}(seed_material, Key, V)$.
5. $reseed_counter = 0$.
6. **Return** (V , Key , $reseed_counter$).

F.3.3 Generating Pseudorandom Bits Using HMAC_DRBG

The implementation returns a *Null* string as the pseudorandom bits if an error has been detected. This function uses the **Update** function specified in Section 10.1.3.2.2.

HMAC_DRBG(...):

Input: integer ($state_handle$, $requested_no_of_bits$, $requested_security_strength$).

Output: string ($status$), bitstring $pseudorandom_bits$.

Process:

Comment: Check for a valid state handle.

1. If $((state_handle > 3) \text{ or } (internal_state(state_handle) = \{\text{Null}, \text{Null}, 0, 0\}))$, then **Return** (“State not available for the indicated $state_handle$ ”, *Null*).

Comment: Get the internal state.

2. $V = internal_state(state_handle).V$, $Key = internal_state(state_handle).Key$, $security_strength = internal_state(state_handle).security_strength$, $reseed_counter = internal_state(state_handle).reseed_counter$.

Comment: Check the validity of the rest of the input parameters.

3. If $(requested_no_of_bits > 7500)$, then **Return** (“Too many bits requested”, *Null*).
4. If $(requested_security_strength > security_strength)$, then **Return** (“Invalid $requested_security_strength$ ”, *Null*).

Comment: Invoke the generate algorithm.

6. $(status, pseudorandom_bits, V, Key, reseed_counter) = \text{Generate_algorithm}(V, Key, reseed_counter, requested_number_of_bits)$.
7. If $(status \neq \text{“Success”})$, then **Return** (“DRBG can no longer be used. Please re-instantiate or reseed”, *Null*).

Comment: Update the internal state.

11. *internal_state (state_handle) = {V, Key, security_strength, reseed_counter}.*
12. **Return** (“Success”, *pseudorandom_bits*).

Generate_algorithm (...):

Input: bitstring (*V, Key*), integer (*reseed_counter, requested_number_of_bits*).
Output: string *status*, bitstring (*pseudorandom_bits, V, Key*), integer *reseed_counter*.

Process:

- 1 If (*reseed_counter* \geq 10,000), then **Return** (“Reseed required”, *Null, V, Key, reseed_counter*).
2. *temp* = *Null*.
- 3 While (**len** (*temp*) < *requested_no_of_bits*) do:
 - 3.1 *V* = **HMAC** (*Key, V*).
 - 3.2 *temp* = *temp* || *V*.
4. *pseudorandom_bits* = Leftmost (*requested_no_of_bits*) of *temp*.
5. (*Key, V*) = **Update** (*additional_input, Key, V*).
6. *reseed_counter* = *reseed_counter* + 1.
7. **Return** (“Success”, *pseudorandom_bits, V, Key, reseed_counter*).

F.4 CTR_DRBG Example

F.4.1 Discussion

This example of **CTR_DRBG** uses AES-128. The reseed and prediction resistance capabilities are available, and a block cipher derivation function using AES-128 is used. Both a personalization string and additional input are allowed. A total of 5 internal states are available. For this implementation, the functions and algorithms are written as separate routines. The **Block_Encrypt** function uses AES-128 in the ECB mode.

The nonce for instantiation (*instantiation_nonce*) consists of a 32-bit incrementing counter (*instantiation_counter*) appended to the personalization string. The nonce is initialized when the DRBG is installed (e.g., by a call to the clock or by setting it to a fixed value) and is incremented for each instantiation.

The internal state contains the values for *V, Key, reseed_counter, security_strength* and *prediction_resistance_flag*, where *V* and *Key* are integers, and all other values are integers.

In accordance with Table 4 in Section 10.2.1, security strengths of 112 and 128 may be supported. Using AES-128, the following definitions are applicable for the instantiate, reseed and generate functions:

1. *highest_supported_security_strength* = 128.
2. Output block length (*outlen*) = 128.
3. Key length (*keylen*) = 128.
4. Required minimum entropy for instantiate and reseed = *security_strength*.
5. Minimum entropy input length (*min_entropy_input_length*) = *security_strength*.
6. Maximum entropy input length (*max_entropy_input_length*) = 1000.
7. Maximum personalization string input length (*max_personalization_string_input_length*) = 500.
8. Maximum additional input length (*max_additional_input_length*) = 500.
9. Seed length (*seedlen*) = 256.
10. Maximum number of bits per request (*max_number_of_bits_per_request*) = 4000.
11. Reseed_interval (*reseed_interval*) = 100,000 requests.

F.4.2 The Update Function

Update (...):

Input: bitstring (*provided_data*, *Key*, *V*).

Output: bitstring (*Key*, *V*).

Process:

1. *temp* = Null.
2. While (**len** (*temp*) < 256) do
 - 3.1 *V* = (*V* + 1) mod 2^{128} .
 - 3.2 *output_block* = **AES_ECB_Encrypt** (*Key*, *V*).
 - 3.3 *temp* = *temp* || *output_block*.
4. *temp* = Leftmost 256 bits of *temp*.
5. *temp* = *temp* \oplus *provided_data*.
6. *Key* = Leftmost 128 bits of *temp*.
7. *V* = Rightmost 128 bits of *temp*.
8. **Return** (*Key*, *V*).

F.4.3 Instantiation of CTR_DRBG

This implementation will return a text message and an invalid state handle (-1) when an error is encountered. **Block_Cipher_df** is the derivation function in Section 9.6.3, and uses AES-128 in ECB mode as the **Block_Encrypt** function.

Note that this implementation does not check the *prediction_resistance_flag*, since the implementation can provide prediction resistance. However, if an application actually wants prediction resistance for a pseudorandom bitstring, the implementation expects that *prediction_resistance_flag* = 1 during instantiation (i.e., an application may not require prediction resistance for an instantiation).

Instantiate_CTR_DRBG (...):

Input: integer (*requested_instantiation_security_strength*, *prediction_resistance_flag*),
bitstring *personalization_string*.

Output: string *status*, integer *state_handle*.

Process:

Comment: Check the validity of the input parameters.

1. If (*requested_instantiation_security_strength* > 128) then **Return** (“Invalid *requested_instantiation_security_strength*”, -1).
2. If (**len** (*personalization_string*) > 500), then **Return** (“*Personalization_string* too long”, -1).
3. If (*requested_instantiation_security_strength* ≤ 112), then *security_strength* = 112
Else *security_strength* = 128.

Comment: Get the entropy input.

4. (*status*, *entropy_input*) = **Get_entropy** (*security_strength*, *security_strength*, 1000).
5. If (*status* ≠ “Success”), then **Return** (“Failure indication returned by the entropy source” || *status*, -1).

Comment: Increment the nonce; actual coding must ensure that it wraps when its storage limit is reached.

6. *instantiation_counter* = *instantiation_counter* + 1.
7. *instantiation_nonce* = *personalization_string* || *instantiation_counter*.
Comment: Invoke the instantiate algorithm.
8. (*V*, *Key*, *reseed_counter*) = **Instantiate_algorithm** (*entropy_input*, *instantiation_nonce*, *personalization_string*).
Comment: Find an available internal state and save the initial values.
9. (*status*, *state_handle*) = **Find_state_space** ().

10. If (*status* ≠ “Success”), then **Return** (“No available state space” || *status*, -1).

Comment: Save the internal state.

11. *internal_state_(state_handle)* = {*V*, *Key*, *reseed_counter*, *security_strength*,
prediction_resistance_flag }.

12. **Return** (“Success”, *state_handle*).

Instantiate_algorithm (...):

Input: bitstring (*entropy_input*, *nonce*, *personalization_string*).

Output: bitstring (*V*, *Key*), integer (*reseed_counter*).

Process:

1. *seed_material* = *entropy_input* || *nonce* || *personalization_string*.
2. *seed_material* = **Block_Cipher_df** (*seed_material*, 256).
3. *Key* = 0^{128} . Comment: 128 bits.
4. *V* = 0^{128} . Comment: 128 bits.
5. (*Key*, *V*) = **Update** (*seed_material*, *Key*, *V*).
6. *reseed_counter* = 1.
7. **Return** (*V*, *Key*, *reseed_counter*).

F.4.4 Reseeding a CTR_DRBG Instantiation

The implementation is designed to return a text message as the *status* when an error is encountered.

Reseed_CTR_DRBG_Instantiation (...):

Input: integer (*state_handle*), bitstring *additional_input*.

Output: string *status*.

Process:

Comment: Check for the validity of
state_handle.

1. If ((*state_handle* > 5) or (*internal_state(state_handle)* = {Null, Null, 0, 0, 0, }),
then **Return** (“State not available for the indicated *state_handle*”).
Comment: Get the internal state values.
2. *V* = *internal_state (state_handle).V*, *Key* = *internal_state (state_handle).Key*,
security_strength = *internal_state (state_handle).security_strength*,
prediction_resistance_flag = *internal_state (state_handle).prediction_resistance_flag*.

3. If (**len** (*additional_input*) > 500), then **Return** (“*Additional_input* too long”).
4. *min_entropy* = *security_strength* + 64.
5. (*status*, *entropy_input*) = **Get_entropy** (*min_entropy*, *min_entropy*, 1000).
6. If (*status* ≠ “Success”), then **Return** (“Failure indication returned by the entropy source” || *status*).
Comment: Invoke the reseed algorithm.
7. (*V*, *Key*, *reseed_counter*) = **Reseed_algorithm** (*V*, *Key*, *reseed_counter*, *entropy_input*, *additional_input*).
Comment: Save the new internal state.
8. *internal_state* (*state_handle*) = {*V*, *Key*, *reseed_counter*, *security_strength*, *reseed_counter*, *prediction_resistance_flag*}.
9. **Return** (“Success”).

Reseed_algorithm (...):

Input: bitstring (*V*, *Key*), integer (*reseed_counter*), bitstring (*entropy_input*, *additional_input*).

Output: bitstring (*V*, *Key*), integer (*reseed_counter*).

Process:

1. *seed_material* = *entropy_input* || *additional_input*.
2. *seed_material* = **Block_Cipher_df** (*seed_material*, 256).
3. (*Key*, *V*) = **Update** (*seed_material*, *Key*, *V*).
4. *reseed_counter* = 1.
5. **Return** (*V*, *Key*, *reseed_counter*).

F.4.5 Generating Pseudorandom Bits Using CTR_DRBG

The implementation returns a *Null* string as the pseudorandom bits if an error has been detected.

CTR_DRBG(...):

Input: integer (*state_handle*, *requested_no_of_bits*, *requested_security_strength*, *prediction_resistance_request*), bitstring *additional_input*.

Output: string *status*, bitstring *pseudorandom_bits*.

Process:

Comment: Check the validity of *state_handle*.

1. If ((*state_handle* > 5) or (*internal_state* (*state_handle*) = {*Null*, *Null*, 0, 0, 0})),

then **Return** (“State not available for the indicated *state_handle*”, *Null*).

Comment: Get the internal state.

2. $V = \text{internal_state}(\text{state_handle}).V$, $\text{Key} = \text{internal_state}(\text{state_handle}).\text{Key}$,
 $\text{security_strength} = \text{internal_state}(\text{state_handle}).\text{security_strength}$,
 $\text{reseed_counter} = \text{internal_state}(\text{state_handle}).\text{reseed_counter}$,
 $\text{prediction_resistance_flag} = \text{internal_state}(\text{state_handle}).\text{prediction_resistance_flag}$.

Comment: Check the rest of the input parameters.

3. If (*requested_no_of_bits* > 4000), then **Return** (“Too many bits requested”, *Null*).

4. If (*requested_security_strength* > *security_strength*), then **Return** (“Invalid *requested_security_strength*”, *Null*).

5. If (*len_additional_input* > 500), then **Return** (“*Additional_input* too long”, *Null*).

6. If ((*prediction_resistance_request* = 1) and (*prediction_resistance_flag* ≠ 1)), then **Return** (“Prediction resistance capability not instantiated”, *Null*).

7. *reseed_required_flag* = 0.

8. If (*reseed_required_flag* = 1) or (*prediction_resistance_request* = 1)), then

- 8.1 *status* = **Reseed_CTR_DRBG_Instantiation** (*state_handle*, *additional_input*).

- 8.2 If (*status* ≠ “Success”), then **Return** (*status*, *Null*).

Comment: Get the new working state values; the administrative information was not affected.

- 8.3 $V = \text{internal_state}(\text{state_handle}).V$, $\text{Key} = \text{internal_state}(\text{state_handle}).\text{Key}$, $\text{reseed_counter} = \text{internal_state}(\text{state_handle}).\text{reseed_counter}$.

- 8.4 *additional_input* = *Null*.

- 8.5 *reseed_request_flag* = 0.

Comment: Generate bits using the generate algorithm.

9. (*status*, *pseudorandom_bits*, *V*, *Key*, *reseed_counter*) = **Generate_algorithm** (*V*, *Key*, *reseed_counter*, *requested_number_of_bits*, *additional_input*).

10. If (*status* ≠ “Success”), then

10.1 *reseed_required_flag* = 1.

10.2 Go to step 8.

Comment: Collect bits.

11. *internal_state* (*state_handle*) = {*V*, *Key*, *security_strength*, *reseed_counter*,
prediction_resistance_flag}.

Comment: Determine the pseudorandom bits
to be returned.

12. **Return** (“Success”, *pseudorandom_bits*).

Generate_algorithm (...):

Input: bitstring (*V*, *Key*), integer (*reseed_counter*, *requested_number_of_bits*)
bitstring *additional_input*.

Output: string *status*, bitstring (*returned_bits*, *V*, *Key*), integer *reseed_counter*.

Process:

1. If (*reseed_counter* > 100,000), then **Return** (“Failure”, *Null*, *V*, *Key*,
reseed_counter).
2. If (*additional_input* ≠ *Null*), then
 - 2.1 *temp* = **len** (*additional_input*).
 - 2.2 If (*temp* > 256), then *additional_input* = **Block_Cipher_df**
(*additional_input*, 256).
 - 2.3 If (*temp* < 256), then *additional_input* = *additional_input* || 0^{256 - *temp*}.
 - 2.4 (*Key*, *V*) = **Update** (*additional_input*, *Key*, *V*).
3. *temp* = *Null*.
4. While (**len** (*temp*) < *requested_number_of_bits*) do:
 - 4.1 *V* = (*V* + 1) mod 2¹²⁸.
 - 4.2 *output_block* = **AES_ECB_Encrypt** (*Key*, *V*).
 - 4.3 *temp* = *temp* || *output_block*.
5. *returned_bits* = Leftmost (*requested_number_of_bits*) of *temp*.
6. *zeros* = 0²⁵⁶.
Comment: Produce a string of 256 zeros.
7. (*Key*, *V*) = **Update** (*zeros*, *Key*, *V*)
8. *reseed_counter* = *reseed_counter* + 1.
9. **Return** (“Success”, *returned_bits*, *V*, *Key*, *reseed_counter*).

F.5 OFB_DRBG Example

F.5.1 Discussion

This example of **OFB_DRBG** uses 3 key TDEA. Full entropy is available, and a block cipher derivation function is not used ; therefore, a nonce is not used. Prediction resistance is supported. A total of 5 internal states are available. A personalization string is allowed during instantiation, and additional input is allowed during reseeding and a request for pseudorandom bit generation. For this implementation, the functions and algorithms are written as separate routines. The **Block_Encrypt** function uses 3 key TDEA in the ECB mode.

The internal state contains the values for *V*, *Key*, *reseed_counter*, *security_strength* and *prediction_resistance_flag*; *V* and *Key* are integers; *reseed_counter*, *security_strength* and *prediction_resistance_flag* are integers.

In accordance with Table 4 in Section 10.2.1, a security strength of 112 is supported. Using 3 key TDEA, the following definitions are applicable for the instantiate, reseed and generate functions:

1. *highest_supported_security_strength* = 112.
2. Output block length (*outlen*) = 64.
3. Key length (*keylen*) = 168.
4. Number of bits for entropy input if full entropy is supported and a derivation function is not used: 232.
5. Minimum entropy input length (*min_entropy_input_length*) = *min_entropy* = 232.
6. Maximum entropy input length (*max_entropy_input_length*) = 232.
7. Maximum personalization string input length (*max_personalization_string_input_length*) = 232.
8. Maximum additional input length (*max_additional_input_length*) = 232.
9. Seed length (*seedlen*) = 232.
10. Maximum number of bits per request (*max_number_of_bits_per_request*) = 1000.
12. Reseed interval (*reseed_interval*) = 10,000 requests.

F.5.2 The Update Function

Update (...):

Input: bitstring (*provided_data*, *Key*, *V*).

Output: bitstring (*Key*, *V*).

Process:

1. $\text{temp} = \text{Null}$.
2. While (**len** (temp) < 232) do
 - 2.1 $V = \text{TDEA_ECB Encrypt} (\text{Key}, V)$.
 - 2.2 $\text{temp} = \text{temp} \parallel V$.
3. $\text{temp} = \text{Leftmost 232 bits of } \text{temp}$.
4. $\text{temp} = \text{temp} \oplus \text{provided_data}$.
5. $\text{Key} = \text{Leftmost 168 bits of } \text{temp}$.
6. $V = \text{Rightmost 64 bits of } \text{temp}$.
7. **Return** (Key, V).

F.5.3 Instantiation of OFB_DRBG

This implementation will return a text message and an invalid state handle (-1) when an error is encountered.

Note that this implementation does not use the *prediction_resistance_flag*, since it is known that prediction resistance is supported. However, if *prediction_resistance_flag* = 1, then a prediction resistance capability is requested for the instantiation.

Instantiate_OFB_DRBG (...):

Input: integer (*requested_instantiation_security_strength*, *prediction_resistance_flag*), bitstring *personalization_string*.

Output: string *status*, integer *state_handle*.

Process:

Comment: Check the validity of the input parameters.

1. If (*requested_instantiation_security_strength* > 112) then **Return** (“Invalid *requested_instantiation_security_strength*”, -1).
2. If (**len** (*personalization_string*) > 232), then **Return** (“*Personalization_string* too long”, -1).
3. *security_strength* = 112.

Comment: Get the entropy input.

4. $(\text{status}, \text{entropy_input}) = \text{Get_entropy} (232, 232, 232)$.
5. If (*status* ≠ “Success”), then **Return** (“Failure indication returned by the entropy source” || *status*, -1).

Comment: Invoke the instantiate algorithm.

6. $(V, \text{Key}, \text{reseed_counter}) = \text{Instantiate_algorithm} (\text{entropy_input},$
152

- personalization_string).*
7. $(status, state_handle) = \text{Find_state_space}()$.
 8. If $(status \neq \text{"Success"})$, then **Return** ("No available state space" || $status, -1$).
Comment: Save the internal state.
 9. $internal_state_ (state_handle) = \{V, Key, reseed_counter, security_strength, prediction_resistance_flag\}$.
 10. **Return** ("Success", $state_handle$).

Instantiate_algorithm (...):

Input: bitstring ($entropy_input, personalization_string$).

Output: bitstring (V, Key), integer $reseed_counter$.

Process:

1. $seed_material = entropy_input \oplus personalization_string$.
2. $Key = 0^{168}$. Comment: 168 bits.
3. $V = 0^{64}$. Comment: 64 bits.
4. $(Key, V) = \text{Update} (seed_material, Key, V)$.
5. $reseed_counter = 1$.
6. **Return** ("Success", $V, Key, reseed_counter$).

F.5.4 Reseeding the OFB_DRBG Instantiation

The implementation is designed to return a text message as the $status$ when an error is encountered.

Reseed_OFB_DRBG_Instantiation (...):

Input: integer $state_handle$, bitstring $additional_input$.

Output: string $status$.

Process:

Comment: Check for the validity of
 $state_handle$.

1. If $((state_handle > 5) \text{ or } (internal_state (state_handle) = \{Null, Null, 0, 0\})$,
then **Return** ("State not available for the indicated $state_handle$ ").
Comment: Get the necessary internal state
values.
2. $V = internal_state (state_handle).V, Key = internal_state (state_handle).Key$,

- security_strength = internal_state(state_handle).security_strength.*
3. If (**len** (*additional_input*) > 232), then **Return** (“*Additional_input* too long”).
Comment: Get the *entropy_input*.
 4. (*status, entropy_input*) = **Get_entropy** (232, 232, 232).
 5. If (*status* ≠ “Success”), then **Return** (“Failure indication returned by the entropy source” || *status*).
Comment: Invoke the reseed algorithm.
 6. (*V, Key, reseed_counter*) = **Reseed_algorithm** (*V, Key, entropy_input, additional_input*).
 7. *internal_state(state_handle).V = V; internal_state(state_handle).Key = Key;*
internal_state(state_handle).reseed_counter = reseed_counter.
 8. **Return** (“Success”).

Reseed_algorithm (...):

Input: bitstring (*V, Key*), bitstring (*entropy_input, additional_input*).

Output: bitstring (*V, Key*), integer *reseed_counter*.

Process:

1. *temp* = **len** (*additional_input*).
Comment: If the *additional_input* < 232, pad with zeros.
2. If (*temp* < 232), then *additional_input* = *additional_input* || 0^{232 - temp}.
3. *seed_material* = *entropy_input* ⊕ *additional_input*.
4. (*Key, V*) = **Update** (*seed_material, Key, V*).
5. *reseed_counter* = 1.
6. **Return** (*V, Key, reseed_counter*).

F.5.5 Generating Pseudorandom Bits using OFB_DRBG

The implementation returns a *Null* string as the pseudorandom bits if an error has been detected. Note that prediction resistance is requested when *prediction_resistance_request* = 1.

OFB_DRBG(...):

Input: integer (*state_handle, requested_no_of_bits, requested_security_strength, prediction_resistance_request*), bitstring *additional_input*.

Output: string *status*, bitstring *pseudorandom_bits*.

Process:

- Comment: Check the validity of *state_handle*.
1. If (*state_handle* > 5) or (*internal_state(state_handle)* = {Null, Null, 0, 0}), then **Return** ("State not available for the indicated *state_handle*", Null).

Comment: Get the internal state values.

 2. $V = \text{internal_state}(\text{state_handle}).V$, $\text{Key} = \text{internal_state}(\text{state_handle}).\text{Key}$,
 $\text{reseed_counter} = \text{internal_state}(\text{state_handle}).\text{reseed_counter}$,
 $\text{security_strength} = \text{internal_state}(\text{state_handle}).\text{security_strength}$,
 $\text{prediction_resistance_flag} = \text{internal_state}(\text{state_handle}).\text{prediction_resistance_flag}$.

Comment: Check the rest of the input parameters.

 3. If (*requested_no_of_bits* > 1000), then **Return** ("Too many bits requested", Null).
 4. If (*requested_security_strength* > *security_strength*), then **Return** ("Invalid *requested_security_strength*", Null).
 5. If (*len(additional_input)* > 232), then **Return** ("Additional_input too long", Null).
 6. If ((*prediction_resistance_request* = 1) and (*prediction_resistance_flag* ≠ 1)), then **Return** ("Invalid *prediction_resistance_request*", Null).
 7. *reseed_required_flag* = 0.
 8. If ((*reseed_required_flag* = 1) or (*prediction_resistance_request* = 1)), then do
 Comment: Reseed.
 - 8.1 *status* = **Reseed_OFB_DRBG_Instantiation** (*state_handle*, *additional_input*).
 - 8.2 If (*status* ≠ "Success"), then **Return** (*status*, Null).
 - 8.3 $V = \text{internal_state}(\text{state_handle}).V$, $\text{Key} = \text{internal_state}(\text{state_handle}).\text{Key}$, $\text{reseed_counter} = \text{internal_state}(\text{state_handle}).\text{reseed_counter}$.
 - 8.4 *additional_input* = Null.
 - 8.5 *reseed_required_flag* = 0.
 9. (*status*, *pseudorandom_bits*, *V*, *Key*, *reseed_counter*) = **Generate_algorithm** (*V*, *Key*, *reseed_counter*, *requested_number_of_bits*, *additional_input*).
 10. If (*status* ≠ "Success"), then

- 10.1 *reseed_required_flag* = 1.
- 10.2 Go to step 8.
11. *internal_state(state_handle)* = {*V*, *Key*, *security_strength*, *reseed_counter*, *prediction_resistance_flag*}.
12. **Return** (“Success”, *pseudorandom_bits*).

Generate_algorithm (...):

Input: bitstring (*V*, *Key*), integer (*reseed_counter*, *requested_number_of_bits*),
bitstring *additional_input*.
integer (*state_handle*, *requested_number_of_bits*).
Output: string *status*, bitstring *returned_bits*.

Process:

1. If (*reseed_counter* > *reseed_interval*), then **Return** (“Reseed required”).
2. If (*additional_input* ≠ Null), then
 - 2.1 *temp* = **len** (*additional_input*).
 - 2.2 If (*temp* < *seedlen*), then *additional_input* = *additional_input* || 0^{*seedlen* - *temp*}.
- 2.3 (*Key*, *V*) = **Update** (*additional_input*, *Key*, *V*).
3. *temp* = Null.
4. While (**len** (*temp*) < *requested_number_of_bits*) do:
 - 4.1 *V* == **TDEA_ECB_Encrypt** (*Key*, *V*).
 - 4.2 *temp* = *temp* || *V*.
5. *returned_bits* = Leftmost (*requested_number_of_bits*) of *temp*.
6. *zeros* = 0²³². Comment: Produce a string of *seedlen* zeros.
7. (*Key*, *V*) = **Update** (*zeros*, *Key*, *V*)
8. *reseed_counter* = *reseed_counter* + 1.
Comment: Save the new values of *V*, *Key* and *reseed_counter*.
9. **Return** (“Success”, *returned_bits*, *V*, *Key*, *reseed_counter*).

F.6 Dual_EC_DRBG Example

F.6.1 Discussion

This example of **Dual_EC_DRBG** allows a consuming application to instantiate using any

of the recommended elliptic curves, depending on the security strength. A reseed capability is available, but prediction resistance is not available. Both a *personalization_string* and *additional_input* are allowed. A total of 10 internal states are provided. For this implementation, the algorithms are provided as inline code within the functions.

The nonce for instantiation (*instantiation_nonce*) consists of a random value with 64-bits of entropy; the nonce is obtained by a separate call to the **Get_entropy** routine.

The internal state contains values for *s*, *curve_type*, *seedlen*, *p*, *a*, *b*, *n*, *P*, *Q*, *block_counter* and *security_strength*. In accordance with Table 5 in Section 10.3.2.1, security strengths of 112, 128, 192 and 256 may be supported. SHA-256 has been selected as the hash function. The following definitions are applicable for the instantiate, reseed and generate functions:

1. *highest_supported_security_strength* = 256.
2. Output block length (*outlen*): See Table.
3. Required minimum entropy for instantiation and reseed = *security_strength*.
4. Minimum entropy input length (*min_entropy_input_length*): See Table.
5. Maximum entropy input length (*max_entropy_input_length*) = 1000.
6. Maximum personalization string length (*max_personalization_string_length*) = 500.
7. Maximum additional input length (*max_additional_input_length*) = 500.
8. Seed length (*seedlen*): See Table.
9. Maximum number of bits per request (*max_number_of_bits_per_request*) = 1000.
10. Reseed interval (*reseed_interval*) = 10,000.

F.6.2 Instantiation of Dual_EC_DRBG

This implementation will return a test message and an invalid state handle (-1) when an **ERROR** is encountered. A DRBG-specific parameter *requested_curve_type* is required (rather than optional) for this implementation for a consuming application to select a curve type. **Hash_df** is specified in Section 9.6.2.

Instantiate_Dual_EC_DRBG (...):

Input: integer (*requested_instantiation_security_strength*), bitstring
personalization_string, integer *requested_curve_type*.

Output: string *status*, integer *state_handle*.

Process:

Comment : Check the validity of the input parameters.

ANS X9.82, Part 3 - DRAFT - March 2005

1. If (*requested_instantiation_security_strength* > 256) then **Return** (“Invalid *requested_instantiation_security_strength*”, -1).
2. If (*len (personalization_string)* > 500), then **Return** (“*personalization_string* too long”, -1).
3. If ((*requested_curve_type* ≠ *Prime_field_curve*) and (*requested_curve_type* ≠ *Random_binary_curve*) and (*requested_curve_type* ≠ *Koblitz_curve*)), then
Return (“Valid curve type not specified”, -1).
Comment : Determine an *m* that is appropriate for the *requested_strength*; this will depend on *curve_type*.
4. If (*requested_curve_type* = *Prime_field_curve*), then
Comment : Choose one of the prime field curves
 - 4.1 If (*requested_instantiation_security_strength* ≤ 112), then
{*security_strength* = 112; *seedlen* = 224; *outlen* = 208;
min_entropy_input_len = 224}
Else if (*requested_instantiation_security_strength* ≤ 128), then
{*security_strength* = 128; *seedlen* = 256; *outlen* = 240;
min_entropy_input_len = 256}
Else if (*requested_instantiation_security_strength* ≤ 192), then
{*security_strength* = 192; *seedlen* = 384; *outlen* = 368;
min_entropy_input_len = 384}
Else {*security_strength* = 256; *seedlen* = 521; *outlen* = 504;
min_entropy_input_len = 528}.
 - 4.2 Select elliptic curve P-*seedlen*, if available. If this curve is not available, then **Return** (“*Prime_field_curve* of the correct length not available”, -1).
5. If (*requested_curve_type* ≠ *Prime_field_curve*), then
Comment: choose one of the binary or Koblitz curves.
 - 5.1 If (*requested_instantiation_security_strength* ≤ 112), then
{*security_strength* = 112; *seedlen* = 233; *outlen* = 216;
min_entropy_input_len = 240}
Else if (*requested_instantiation_security_strength* ≤ 128), then
{*security_strength* = 128; *seedlen* = 283; *outlen* = 264;

```

min_entropy_input_len = 288}

Else if (requested_instantiation_security_strength ≤ 192), then
    {security_strength = 192; seedlen = 409; outlen = 392;
     min_entropy_input_length = 416}

Else {security_strength = 256; seedlen = 571; outlen = 552;
      min_entropy_input_length = 576}

5.2 p = 0.

5.3 If (curve_type = Random binary curve), then select elliptic curve B-
    seedlen; if this curve is not available, then Return
    ("Random_binary_curve of the correct length not available", -1).

Else select elliptic curve K-seedlen; if this curve is not available, then
Return ("Koblitz_curve of the correct length not available", -1).

6 Set the point P to the generator G for the curve, and set n to the order of G.

7. Set the corresponding point Q from Annex A.1.

Comment: Request entropy_input.

8. (status, entropy_input) = Get_entropy (security_strength,
   min_entropy_input_length, 1000).

9. If (status ≠ "Success"), then Return ("Failure indication returned by the
   entropy_input source:" || status, -1).

10. (status, instantiation_nonce) = Get_entropy (64, 64, 1000).

11. If (status ≠ "Success"), then Return ("Failure indication returned by the
   random nonce source:" || status, -1).

Comment : Perform the instantiate algorithm.

12. seed_material = entropy_input || instantiation_nonce || personalization_string.

13. s = Hash_df (seed_material, seedlen).

14. block_counter = 0.

Comment: Find an unused internal state and
save the initial values.

15. (status, state_handle) = Find_state_space ().

16. If (status ≠ "Success"), then Return (status, -1).

17. internal_state (state_handle) = {s, curve_type, m, p, a, b, n, P, Q,
   block_counter, security_strength}.

18. Return ("Success", state_handle).

```

F.6.3 Reseeding a Dual_EC_DRBG Instantiation

The implementation is designed to return a text message as the status when an error is encountered.

Reseed_Dual_EC_DRBG_Instantiation (...):

Input: integer *state_handle*, string *additional_input_string*.

Output: string *status*.

Process:

Comment: Check the input parameters.

1. If ((*state_handle* > 10) or (*internal_state* (*state_handle*).*security_strength* = 0)), then **Return** (“State not available for the *state_handle*”).
2. If (**len** (*additional_input*) > 500), then Return (“Additional_input too long”).

Comment: Get the appropriate *state* values for the indicated *state_handle*.

3. *s* = *internal_state* (*state_handle*).*s*, *seedlen* = *internal_state* (*state_handle*).*seedlen*, *security_strength* = *internal_state* (*state_handle*).*security_strength*.

Comment: Request new *entropy_input* with the appropriate entropy and bit length.

3. (*status*, *entropy_input*) = **Get_entropy** (*security_strength*, *min_entropy_input_length*, 1000).

4. If (*status* ≠ “Success”), then **Return** (“Failure indication returned by the entropy source:”|| *status*).

Comment: Perform the reseed algorithm.

5. *seed_material* = **pad8** (*s*) || *entropy_input* || *additional_input*.

6. *s* = **Hash_df** (*seed_material*, *seedlen*).

7. *block_counter* = 0.

Comment: Update the changed values in the *state*.

8. *internal_state* (*state_handle*).*s* = *s*.

9. *internal_state*.*block_counter* = *block_counter*.

10. **Return** (“Success”).

F.6.4 Generating Pseudorandom Bits Using Dual_EC_DRBG

The implementation returns a *Null* string as the pseudorandom bits if an error is encountered.

Dual_EC_DRBG (...):

Input: integer (*state_handle*, *requested_security_strength*, *requested_no_of_bits*),
bitstring *additional_input*.

Output: string *status*, bitstring *pseudorandom_bits*.

Process:

Comment: Check for an invalid *state_handle*.

1. If $((state_handle > 10) \text{ or } (internal_state(state_handle) = 0))$, then **Return** (“State not available for the *state_handle*”, *Null*).

Comment: Get the appropriate *state* values for the indicated *state_handle*.

2. $s = internal_state(state_handle).s$, $seedlen = internal_state(state_handle).seedlen$, $security_strength = internal_state(state_handle).security_strength$, $P = internal_state(state_handle).P$, $Q = internal_state(state_handle).Q$, $block_counter = internal_state(state_handle).block_counter$.

Comment: Check the rest of the input parameters.

3. If $(requested_number_of_bits > 1000)$, then **Return** (“Too many bits requested”, *Null*).
4. If $(requested_security_strength > security_strength)$, then **Return** (“Invalid requested_strength”, *Null*).
5. If $(\text{len } additional_input) > 500$, then **Return** (“Additional_input too long”, *Null*).

Comment: Check whether a reseed is required.

6. If $(block_counter + \lceil \frac{requested_number_of_bits}{outlen} \rceil) > 10,000$, then

6.1 **Reseed_Dual_EC_DRBG_Instantiation** (*state_handle*, *additional_input*).

6.2 *additional_input* = *Null*.

- 6.3 $s = \text{internal_state}(\text{state_handle}).s$, $\text{seedlen} = \text{internal_state}(\text{state_handle}).\text{seedlen}$, $\text{security_strength} = \text{internal_state}(\text{state_handle}).\text{security_strength}$, $P = \text{internal_state}(\text{state_handle}).P$, $Q = \text{internal_state}(\text{state_handle}).Q$, $\text{block_counter} = \text{internal_state}(\text{state_handle}).\text{block_counter}$.
- Comment: Execute the generate algorithm.
7. If ($\text{additional_input} = \text{Null}$) then $\text{additional_input} = 0$
 - Comment: additional_input set to m zeroes.
- Else $\text{additional_input} = \text{Hash_df}(\text{pad8}(\text{additional_input}), \text{seedlen})$.
 - Comment: Produce $\text{requested_no_of_bits}$, outlen bits at a time:
8. $\text{temp} = \text{the Null string.}$
9. $i = 0.$
10. $t = s \oplus \text{additional_input.}$
11. $s = \varphi(x(t * P)).$
12. $r = \varphi(x(s * Q)).$
13. $\text{temp} = \text{temp} \parallel (\text{rightmost } \text{outlen} \text{ bits of } r).$
14. $\text{additional_input} = 0^{\text{seedlen}}$.
 - Comment: seedlen zeroes; additional_input is added only on the first iteration.
15. $\text{block_counter} = \text{block_counter} + 1.$
16. $i = i + 1.$
17. If ($\text{len}(\text{temp}) < \text{requested_no_of_bits}$), then go to step 11.
18. $\text{pseudorandom_bits} = \text{Truncate}(\text{temp}, i \times \text{outlen}, \text{requested_no_of_bits})$.
 - Comment: Update the changed values in the state .
19. $\text{internal_state}.s = s.$
20. $\text{internal_state}.block_counter = \text{block_counter}.$
21. **Return** (“Success”, pseudorandom_bits).

F.7 MS_DRBG Example

F.7.1 Discussion

This example of **MS_DRBG** allows a consuming application to request specific values for e and outlen . A reseed capability is available, but prediction resistance is dependent on the

user's system. Both a *personalization_string* and *additional_input* are allowed. A total of 5 internal states are provided. For this implementation, the handling of the DRBG-specific parameters and the algorithms are provided as separate routines.

The nonce for instantiation consists of a random value with 64-bits of entropy; the nonce is obtained by increasing the call for entropy bits via the **Get_entropy** call by 64 bits (i.e., by adding 64 bits to the *security_strength* value).

The internal state contains values for *n*, *e*, *seedlen*, *outlen*, *S*, *block_counter*, *security_strength* and *prediction_resistance_flag*.

In accordance with Table 6 in Section 10.3.3.1, security strengths of 112 and 128 may be supported. SHA-1 has been selected as the hash function. The following definitions are applicable for the instantiate, reseed and generate functions :

1. *highest_supported_security_strength*: Depends on the requested security strength.
2. Output block length (*outlen*): 8, unless otherwise requested using *requested_outlen*.
3. Required minimum entropy for instantiation = *security_strength* + 64 (includes the random nonce).
4. Required minimum entropy for reseed = *security_strength*.
5. Minimum entropy input length (*min_entropy_input_length*): *min_entropy*.
6. Maximum entropy input length (*max_entropy_input_length*) = 5000 bits.
7. Maximum personalization string length (*max_personalization_string_length*) = 500 bits.
8. Maximum additional input length (*max_additional_input_length*) = 500 bits.
9. Number of hard bits = 11.
10. Seed length (*seedlen*): $\lg(n) - 8$.
11. Maximum number of bits per request (*max_number_of_bits_per_request*) = 200,000 bits.
12. Reseed interval (*reseed_interval*) = 25,000 blocks of *outlen* bits.

F.7.2 Instantiation of MS_DRBG

This implementation will return a test message and an invalid state handle (-1) when an **ERROR** is encountered. DRBG-specific parameters (*requested_e* and *requested_outlen*) are provided that will allow a consuming application to optionally select the values for *e* and *outlen*. **Hash_df** is specified in Section 9.6.2.

If *prediction_resistance_flag* = 1, then a prediction resistance capability is requested for the instantiation. If the user's system is capable of handling prediction resistance (e.g., a source of randomness is readily available), the user has been instructed to indicate the ability to provide prediction resistance by setting *prediction_resistance_capability* = 1

during system configuration.

Let **Get_random_modulus** be a function that gets a random modulus n that meets the criteria specified in Section 10.3.3.2.3, step 5.5.

Instantiate_MS_DRBG (...):

Input: integer (*requested_instantiation_security_strength*,
prediction_resistance_flag), bitstring *personalization_string*, integer
(*requested_e*, *requested_outlen*).

Output: string *status*, integer *state_handle*.

Process:

1. If (*requested_instantiation_security_strength* > 128), then **Return** (“Invalid *requested_instantiation_security_strength*”, -1).
2. If ((*prediction_resistance_flag* = 1) and (*prediction_resistance_capability* ≠ 1)), then **Return** (“Cannot support prediction resistance”, -1).
3. If (*len (personalization_string)* > 500), then **Return** (“Personalization_string too long”, -1).
4. If (*requested_instantiation_security_strength* ≤ 112), then *security_strength* = 112
Else *security_strength* = 128.
5. (*status, n, e, seedlen, outlen*) = **Get_DRBG_specific_parameters** (*security_strength*, *requested_e*, *requested_outlen*).

Comment: Get *entropy_input*.

6. *min_entropy* = *security_strength* + 64.
7. (*status, entropy_input*) = **Get_entropy** (*min_entropy*, *min_entropy*, 5000).
8. If (*status* ≠ “Success”), then **Return** (“Failure indication returned by the entropy source”, -1).
9. (*S, block_counter*) = **Instantiate_algorithm** (*entropy_input*,
personalization_string, *seedlen*).
Comment: Find an empty state in the state space.

10. (*status, state_handle*) = **Find_state_space** ().
11. If (*status* ≠ “Success”), **Return** (*status*, -1).

ANS X9.82, Part 3 - DRAFT - March 2005

Comment: Store all values in *state*.

12. *internal_state* (*state_handle*) = {*n*, *e*, *seedlen*, *outlen*, *S*, *block_counter*,
security_strength, *prediction_resistance_flag*}.

13. **Return** (“Success”, *state_handle*).

Get_DRBG_specific_parameters (...).

Input: integer (*security_strength*, *requested_e*, *requested_outlen*).

Output: string (*status*), integer (*n*, *e*, *seedlen*, *outlen*).

Process:

Comment: Determine modulus size (i.e.,
 $\lg(n)$).

1. If (*security_strength* = 112) then *modulus_size* = 2048

Else *modulus_size* = 3072.

Comment: Select the exponent *e*.

2. If (*requested_e* = 0) or is not provided, then *e* = 3

Else

2.1 *e* = *requested_e*.

2.2 If ((*e* < 3) or (*e* > ($2^{\lg(n)-1} - (2 \times 2^{1/2 \lg(n)})$)) or (*e* mod 2 = 0)), then
Return (“Invalid *requested_e*”, -1).

Comment: Determine *outlen*.

3. If (*requested_outlen* = 0) or is not provided, then *outlen* = 8

Else

3.1 *outlen* = *requested_outlen*.

3.2 If ((*outlen* < 1) or (*outlen* > $\min(\lfloor \lg(n) - 2 * \text{security_strength} \rfloor, \lfloor \lg(n) * (1 - 2/e) \rfloor)$) or (*outlen* mod 8 ≠ 0)), then **Return**
 (“Inappropriate value for *requested_outlen*”, -1).

4. *seedlen* = *modulus_size* – *outlen*. Comment: Determine the seed length.

Comment: Select the modulus *n*.

5. (*status*, *n*) = **Get_random_modulus** (*modulus_size*, *e*).

6. If (*status* ≠ “Success”), then **Return** (“Failed to produce an appropriate
modulus”, -1).

7. **Return** (“Success”, *n*, *e*, *seedlen*, *outlen*).

Instantiate_algorithm (...):

Input: bitstring (*entropy_input*, *personalization_string*), integer *seedlen*.

Output: integer (S , $block_counter$).

Process:

1. $seed_material = entropy_input \parallel personalization_string$.
2. $S = \text{Hash_df}(seed_material, seedlen)$.
3. $block_counter = 0$.
4. **Return** (S , $block_counter$).

F.7.3 Reseeding an MSDRBG Instantiation

The implementation is designed to return a text message as the status when an error is returned.

Reseed_MS_DRBG (...):

Input: integer $state_handle$, bitstring $additional_input$.

Output: string $status$.

Process:

1. If $((state_handle > 5) \text{ or } (internal_state(state_handle).security_strength = 0))$, then **Return** ("State not available for the indicated $state_handle$ ").
Comment: Get the required $state$ values for the indicated $state_handle$.
2. $S = internal_state(state_handle).S$, $seedlen = internal_state(state_handle).seedlen$, $security_strength = internal_state(state_handle).security_strength$.
3. If $(\text{len}(additional_input) > 500)$, then **Return** ("Additional_input too long", -1).
4. $min_entropy = security_strength$.
5. $(status, entropy_input) = \text{Get_entropy}(min_entropy, min_entropy, 5000)$.
6. If $(status \neq \text{"Success"})$, then **Return** ("Failure indication returned by the $entropy_input$ source").
7. $(S, block_counter) = \text{Reseed_algorithm}(entropy_input, additional_input, S, seedlen)$.
8. $internal_state(state_handle).S = S$, $internal_state(state_handle).block_counter = block_counter$.
9. **Return** ("Success").

Reseed_algorithm (...):

Input: bitstring ($entropy_input$, $additional_input$), integer (S , $seedlen$).

Output: integer ($S, block_counter$).

Process:

1. $seed_material = S \parallel entropy_input \parallel additional_input$.
2. $S = \text{Hash_df}(seed_material, seedlen)$.
3. $block_counter = 0$.
4. **Return** ($S, block_counter$).

F.7.4 Generating Pseudorandom Bits Using MS_DRBG

The implementation returns a *Null* string as the pseudorandom bits if an error is encountered. If prediction resistance is needed, then *prediction_resistance_request* = 1.

MS_DRBG (...):

Input: integer (*state_handle*, *requested_no_of_bits*, *requested_security_strength*, *prediction_resistance_request*), bitstring *additional_input*.

Output: string *status* , bitstring *pseudorandom_bits*.

Process:

1. If $((state_handle > 5) \text{ or } (internal_state(state_handle).security_strength = 0))$, then **Return** ("State not available for the indicated *state_handle*", *Null*).
Comment: Get the appropriate *state* for the indicated *state_handle*.
2. $S = internal_state(state_handle).S, n = internal_state(state_handle).n, e = internal_state(state_handle).e, outlen = internal_state(state_handle).outlen, seedlen = internal_state(state_handle).seedlen, security_strength = internal_state(state_handle).security_strength, block_counter = internal_state(state_handle).block_counter, prediction_resistance_flag = internal_state(state_handle).prediction_resistance_flag$.
3. If $(requested_no_of_bits > (25000 \times outlen))$, then **Return** ("Too many bits requested", *Null*).
4. If $(requested_security_strength > security_strength)$, then **Return** ("Invalid requested_security_strength", *Null*).
5. If $(\text{len}(additional_input) > 500)$, then **Return** ("Additional_input too long", *Null*).
6. If $((prediction_resistance_request = 1) \text{ and } (prediction_resistance_flag} \neq 1)$, then **Return** ("Prediction resistance capability not instantiated", *Null*).
7. $reseed_required_flag = 0$.
8. If $((reseed_required_flag = 1) \text{ or } (prediction_resistance_request = 1))$, then

- 8.1 $\text{status} = \text{Reseed_MS_DRBG}(\text{state_handle}, \text{additional_input})$.
 - 8.2 $S = \text{internal_state}(\text{state_handle}).S$, $\text{block_counter} = \text{internal_state}(\text{state_handle}).\text{block_counter}$.
 - 8.3 $\text{additional_input} = \text{Null}$.
 - 8.4 $\text{reseed_request_flag} = 0$.
 9. $(\text{status}, \text{pseudorandom_bits}, S, \text{block_counter}) = \text{Generate_algorithm}(n, e, \text{seedlen}, \text{outlen}, S, \text{block_counter}, \text{requested_number_of_bits}, \text{additional_input})$.
 10. If ($\text{status} \neq \text{"Success"}$), then
 - 10.1 $\text{reseed_required_flag} = 1$.
 - 10.2 Go to step 8.
 11. $\text{internal_state}.S = S$, $\text{internal_state}.block_counter = block_counter$.
 12. **Return** ("Success", pseudorandom_bits).
- Generate_algorithm (...):**
- Input:** integer $(n, e, \text{seedlen}, \text{outlen}, S, \text{block_counter}, \text{requested_number_of_bits})$, bitstring additional_input .
- Output:** string status , bitstring pseudorandom_bits .
- Process:**
1. If $\left(\left(\text{reseed_counter} + \left\lceil \frac{\text{requested_number_of_bits}}{\text{outlen}} \right\rceil \right) > 25,000 \right)$, then
Return ("Reseed required", Null).
 2. If ($\text{additional_input} = \text{Null}$), then $\text{additional_input} = 0$
Else $\text{additional_input} = \text{Hash_df}(\text{pad8}(\text{additional_input}), \text{seedlen})$.
 3. $\text{temp} = \text{the Null string}$.
 4. $i = 0$.
 5. $s = S \oplus \text{additional_input}$.
 6. $S = [(s^e \bmod n) / 2^{\text{seedlen}}]$. Comment: S is an seedlen -bit number.
 7. $R = (s^e \bmod n) \bmod 2^{\text{outlen}}$. Comment: R is an outlen -bit number.
 8. $\text{temp} = \text{temp} \parallel R$.
 9. $\text{additional_input} = 0^{\text{seedlen}}$.
 10. $i = i + 1$.

ANS X9.82, Part 3 - DRAFT - March 2005

11. *block_counter* = *block_counter*+1.
12. If (**len** (*temp*) < *requested_no_of_bits*), then go to step 6.
13. *pseudorandom_bits* = **Truncate** (*temp*, *i* × *outlen*, *requested_no_of_bits*).
14. **Return** (“Success”, *pseudorandom_bits*).

ANNEX G: (Informative) Bibliography

- [1] Handbook of Applied Cryptography; Menezes, van Oorschot and Vanstone; CRC Press, 1997
- [2] Applied Cryptography, Schneier, John Wiley & Sons, 1996
- [3] RFC 1750, Randomness Recommendations for Security, IETF Network Working Group; Eastlake, Crocker and Schiller; December 1994.
- [4] Cryptographic Random Numbers, Ellison, submission for IEEE P1363.
- [5] Cryptographic Randomness from Air Turbulence in Disk Drives; Davis, Ihaka and Fenstermacher.
- [6] Yarrow-160: Notes on the Design and Analysis of the Yarrow Cryptographic Pseudorandom Number Generator; Kelsey, Schneier, and Ferguson.
- [7] The Intel® Random Number Generator; Cryptography Research, Inc.; White paper prepared for Intel Corporation; Jun and Kocher; April 22, 1999.
- [8] Federal Information Processing Standard 140-2, *Security Requirements for Cryptographic Modules*, May 25, 2001.
- [9] National Institute of Standards and Technology Special Publication 800-38A, *Recommendation for Block Cipher Modes of Operation - Methods and Techniques*, December 2001