Guideline for Using Cryptographic Standards in the Federal Government:

Cryptographic Mechanisms

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Abstract

This document is intended to provide guidance to the Federal Government for using cryptography and NIST's cryptographic standards to protect sensitive, but unclassified digitized information during transmission and while in storage. The cryptographic methods and services to be used are discussed.

Keywords

Acknowledgments

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1.0   INTRODUCTION

1.1   Overview and Purpose

In today's environment of increasingly open and interconnected systems and networks and the use of mobile devices, network and data security are essential for the optimum safe use of this information technology. Cryptographic techniques should be considered for the protection of data that is sensitive, has a high value, or is vulnerable to unauthorized disclosure or undetected modification during transmission or while in storage.

Cryptography is a branch of mathematics that is based on the transformation of data and can be used to provide several security services: confidentiality, identity authentication, data integrity authentication, and source authentication, and also to support non-repudiation.

- *Confidentiality* is the property whereby sensitive information is not disclosed to unauthorized entities. Confidentiality can be provided by a cryptographic process called *encryption*.

- *Data integrity* is a property whereby data has not been altered in an unauthorized manner since it was created, transmitted or stored. The process of determining the integrity of the data is called *data integrity authentication* or *integrity verification*.

- *Identity authentication* is used to provide assurance of the identity of an entity interacting with a system.

- *Source authentication* is a process that provides assurance of the source of information to a receiving entity. A special case of source authentication is called *non-repudiation*, whereby support for assurance of the source of the information is provided to a third party.

This document is one part in a series of documents intended to provide guidance to the Federal Government for using cryptography to protect its sensitive, but unclassified digitized information during transmission and while in storage; hereafter, the shortened term "sensitive" will be used to refer to this class of information. Other sectors are invited to use this guidance on a voluntary basis. The following are the initial publications in the Special Publication (SP) 800-175 series. Additional documents may be provided in the future.

- [SP 800-175A][1] provides guidance on the determination of requirements for using cryptography. It includes the laws and regulations for the protection of the Federal Government's sensitive information, guidance for the conduct of risk assessments to determine what needs to be protected and how best to protect that information, and a discussion of the required security-related documents (e.g., various policy and practice documents).

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[1] SP 800-175A, *Guideline for Using Cryptographic Standards in the Federal Government: Directives, Mandates and Policies.*

38   • SP 800-175B (this document) discusses the cryptographic methods and services
39   available for the protection of the Federal Government's sensitive information and
40   provides an overview of NIST's cryptographic standards.

1.2   Audience

42   This document is intended for federal employees and others who are responsible for
43   providing and using cryptographic services to meet identified security requirements. This
44   document might be used by:

45   • Program managers responsible for selecting and integrating cryptographic
46   mechanisms into a system;

47   • A technical specialist that has been requested to select one or more cryptographic
48   methods/techniques to meet a specified requirement;

49   • A procurement specialist developing a solicitation for a system, network or service
50   that will require cryptographic methods to perform security functionality; and

51   • Users of cryptographic services.

52   The goal is to provide these individuals with sufficient information to allow them to make
53   informed decisions about the cryptographic methods that will meet their specific needs to
54   protect the confidentiality and integrity of data that is transmitted and/or stored in a system
55   or network, as well as to obtain assurance of its authenticity.

56   This document is not intended to provide information on the federal procurement process
57   or to provide a technical discussion on the mathematics of cryptography and cryptographic
58   algorithms.

1.3   Scope

60   This document limits its discussion of cryptographic methods to those that conform to
61   Federal Information Processing Standards (FIPS) and NIST Special Publications (SPs),
62   which are collectively discussed as NIST "standards" in this document. While the Federal
63   Government is required to use these standards when applicable, industry and national and
64   international standards bodies have also adopted these cryptographic methods.

65   This document provides information on selecting and using cryptography in new or
66   existing systems.

1.4   Background

68   The use of cryptography relies upon two basic components: an *algorithm* and a *key*. The
69   algorithm is a mathematical function, and the key is a parameter used during the
70   cryptographic process. The algorithm and key are used together to apply cryptographic
71   protection to data (e.g., to encrypt the data or to generate a digital signature) and to remove
72   or check the protection (e.g., to decrypt the encrypted data or to verify the digital signature).
73   The security of the cryptographic protection relies on the secrecy of the key. Security
74   should not rely on the secrecy of the algorithm, as the algorithm specification may be
75   publicly available.

76 In order to use a cryptographic algorithm, cryptographic keys must be "in place," i.e., keys
77 must be established for and/or between parties that intend to use cryptography. Keys may
78 be established either manually (e.g., via a trusted courier) or using an automated method.
79 However, when an automated method is used, source authentication is required for the
80 participating entities that relies on an established trust infrastructure, such as a Public Key
81 Infrastructure (PKI) or on a manually distributed authentication key.

82 In general, keys used for one purpose (e.g., the generation of digital signatures) must not
83 be used for another purpose (e.g., for key establishment) because the use of the same key
84 for two different cryptographic processes may weaken the security provided by one or both
85 of the processes. See Section 5.2 in SP 800-57, Part 1[2] for further information.

1.5   Terms and Definitions

87 The following terms and definitions are used in this document. In general, the definitions
88 are drawn from FIPS and NIST Special Publications.

Algorithm	A clearly specified mathematical process for computation; a set of rules that, if followed, will give a prescribed result.
Approved	FIPS-Approved and/or NIST-recommended. An algorithm or technique that is either 1) specified in a FIPS or NIST recommendation, or 2) specified elsewhere and adopted by reference in a FIPS or NIST Recommendation.
Asymmetric-key algorithm	See *public-key algorithm*.
Authentication	A process that provides assurance of the source and integrity of information that is communicated or stored or the identity of an entity interacting with a system.
	Note that in common practice, the term "authentication" is used to mean either source or identity authentication only. This document will differentiate the multiple uses of the word by the terms *source authentication*, *identity authentication* or *integrity authentication*, where appropriate.
Bit string	An ordered sequence of 0's and 1's. Also called a bit string.
Block cipher algorithm	A family of functions and their inverse functions that is parameterized by cryptographic keys; the functions map bit strings of a fixed length to bit strings of the same length.
Certificate (or public key certificate)	A set of data that uniquely identifies an entity, contains the entity's public key and possibly other information, and is digitally signed by a trusted party, thereby binding the public key to the

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[2] SP 800-57 Part 1, *Recommendation for Key Management: General Guideline.*

	entity identified in the certificate. Additional information in the certificate could specify how the key is used and the validity period of the certificate.
Certificate Revocation List (CRL)	A list of revoked but unexpired certificates issued by a Certification Authority.
Certification Authority (CA)	The entity in a public key infrastructure (PKI) that is responsible for issuing certificates to certificate subjects and exacting compliance to a PKI policy.
Ciphertext	Data in its encrypted form.
Compromise	The unauthorized disclosure, modification, substitution or use of sensitive data (e.g., a secret key, private key or secret metadata).
Confidentiality	The property that sensitive information is not disclosed to unauthorized entities, i.e., the secrecy of key information is maintained.
Cross certify	The establishment of a trust relationship between two Certification Authorities (CAs) through the signing of each other's public key in certificates; referred to as a "cross-certificate."
Cryptographic algorithm	A well-defined computational procedure that takes variable inputs, including a cryptographic key (if applicable), and produces an output.
Cryptographic boundary	An explicitly defined continuous perimeter that establishes the physical bounds of a cryptographic module and contains all the hardware, software and/or firmware components of a cryptographic module.
Cryptographic checksum	A mathematical value created using a cryptographic algorithm that is assigned to data and later used to test the data to verify that the data has not changed.
Cryptographic hash function	A function that maps a bit string of arbitrary length to a fixed-length bit string. **Approved** hash functions satisfy the following properties: 1. (One-way) It is computationally infeasible to find any input that maps to any pre-specified output, and 2. (Collision resistant) It is computationally infeasible to find any two distinct inputs that map to the same output.

Cryptographic key	A parameter used in conjunction with a cryptographic algorithm that determines its operation in such a way that an entity with knowledge of the key can reproduce or reverse the operation, while an entity without knowledge of the key cannot. Examples include: 1. The transformation of plaintext data into ciphertext data, 2. The transformation of ciphertext data into plaintext data, 3. The computation of a digital signature from data, 4. The verification of a digital signature, 5. The computation of a message authentication code (MAC) from data, 6. The verification of a MAC received with data , and 7. The computation of a shared secret that is used to derive keying material.
Cryptographic module	The set of hardware, software and/or firmware that implements **approved** security functions (including cryptographic algorithms and key generation) and is contained within a cryptographic boundary.
Cryptographic primitive	A low-level cryptographic algorithm used as a basic building block for higher-level cryptographic algorithms.
Cryptography	The discipline that embodies the principles, means and methods for providing information security, including confidentiality, data integrity, source authentication and non-repudiation.
Cryptoperiod	The time span during which a specific key is authorized for use or in which the keys for a given system may remain in effect.
Data integrity	A property whereby data has not been altered in an unauthorized manner since it was created, transmitted or stored.
Decryption	The process of changing ciphertext into plaintext using a cryptographic algorithm and key.
Digital signature	The result of a cryptographic transformation of data that, when properly implemented, provides the services of: 1. Source authentication, 2. Data integrity, and 3. Support for signer non-repudiation.

Digital Signature Algorithm (DSA)	A public-key algorithm that is used for the generation and verification of digital signatures.
Domain parameters	The parameters used with a cryptographic algorithm that are common to a domain of users.
Elliptic Curve Digital Signature Algorithm (ECDSA)	A digital signature algorithm that is an analog of DSA using elliptic curves.
Encryption	The process of changing plaintext into ciphertext using a cryptographic algorithm for the purpose of security or privacy.
Entity	An individual (person), organization, device or process.
Ephemeral key pair	A short-term key pair that is generated when needed; the public key of an ephemeral key pair is not provided in a public key certificate, unlike static public keys which often are.
Function	Used interchangeability with algorithm in this document.
Hash function	See *cryptographic hash function*.
Hash value	The result of applying a hash function to information; also called a message digest.
Identity authentication	The process of providing assurance about the identity of an entity interacting with a system. Also see *Source authentication*.
Initialization Vector (IV)	A vector used in defining the starting point of a cryptographic process.
Integrity	The property that data has not been modified or deleted in an unauthorized and undetected manner.
Integrity authentication (integrity verification)	The process of determining the integrity of the data.
Interoperability	The ability of one entity to communicate with another entity.
Key	See *cryptographic key*.
Key agreement	A (pair-wise) key-establishment procedure where secret keying material is generated from information contributed by two participants, so that no party can predetermine the value of the

	secret keying material independently from the contributions of the other party. Contrast with key-transport.
Key derivation	The process by which keying material is derived from either a pre-shared key, or a shared secret (i.e, from a key-agreement scheme), along with other information.
Key establishment	The procedure that results in keying material that is shared among different entities.
Key information	Information about a key that includes the keying material and associated metadata relating to that key.
Key management	The activities involving the handling of cryptographic keys and other related security parameters (e.g., IVs and counters) during the entire life cycle of the keys, including the generation, storage, establishment, entry and output, use and destruction.
Key pair	A public key and its corresponding private key; a key pair is used with a public key (asymmetric-key) algorithm.
Key transport	A key-establishment procedure whereby one party (the sender) selects a value for the secret keying material and then securely distributes that value to another party (the receiver). Contrast with key agreement.
Key wrapping	A method of cryptographically protecting the confidentiality and integrity of keys using a symmetric-key algorithm.
Key-wrapping key	A symmetric key used to provide confidentiality and integrity protection for other keys.
Keying material	A cryptographic key and other parameters (e.g., IVs or domain parameters) used with a cryptographic algorithm. When keying material is derived as specified in SP 800-56C[3] and SP 800-108:[4] Data represented as a binary string such that any non-overlapping segments of the string with the required lengths can be used as secret keys, secret initialization vectors and other secret parameters.
Keying relationship, cryptographic	The state existing between two entities such that they share at least one cryptographic key.

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[3] SP 800-56C, *Recommendation for Key Derivation through Extraction-then-Expansion*.

[4] SP 800-108, *Recommendation for Key Derivation Using Pseudorandom Functions*.

Message Authentication Code (MAC)	A cryptographic checksum on data that uses an **approved** security function and a symmetric key to detect both accidental and intentional modifications of data.
Message digest	See *hash value*.
Metadata	The information associated with a key that describes its specific characteristics, constraints, acceptable uses, ownership, etc. Sometimes called the key's attributes.
Mode of operation	An algorithm that uses a block cipher algorithm as a cryptographic primitive to provide a cryptographic service, such as confidentiality or authentication.
NIST standard	Federal Information Processing Standard (FIPS) or Special Publication (SP).
Non-repudiation	A service using a digital signature that is used to support a determination of whether a message was actually signed by a given entity.
Owner of a certificate	The entity that is responsible for managing the certificate, including requesting, replacing and revoking the certificate if and when required. The certificate owner is not necessarily the subject entity associated with the public key in the certificate (i.e., the key pair owner).
Owner of a key or key pair	One or more entities that are authorized to use a symmetric key or the private key of a key pair.
Plaintext	Data that has not been encrypted. Intelligible data that has meaning and can be understood without the application of decryption.
Pre-shared key	A secret key that has been established between the parties who are authorized to use it by means of some secure method (e.g., using a secure manual-distribution process or automated key-establishment scheme).
Primitive	See *Cryptographic primitive*.
Private key	A cryptographic key used with a public key cryptographic algorithm that is uniquely associated with an entity and is not made public. In an asymmetric (public) key cryptosystem, the private key is associated with a public key. Depending on the algorithm, the private key may be used to: 1. Compute the corresponding public key,

	2. Compute a digital signature that may be verified by the corresponding public key,
	3. Decrypt data that was encrypted by the corresponding public key, or
	4. Compute a shared secret during a key-agreement process.
Protocol	A set of rules used by two or more communicating entities that describe the message order and data structures for information exchanged between the entities.
Public key	A cryptographic key used with a public-key cryptographic algorithm, that is uniquely associated with an entity and that may be made public. In an asymmetric (public) key cryptosystem, the public key is associated with a private key. The public key may be known by anyone and, depending on the algorithm, may be used to: 1. Verify a digital signature that is signed by the corresponding private key, 2. Encrypt data that can be decrypted by the corresponding private key, or 3. Compute a shared secret during a key-agreement process.
Public key (asymmetric) cryptographic algorithm	A cryptographic algorithm that uses two related keys, a public key and a private key. The two keys have the property that determining the private key from the public key is computationally infeasible.
Public Key Infrastructure (PKI)	A framework that is established to issue, maintain and revoke public key certificates.
Random bit generator (RBG)	A device or algorithm that outputs a sequence of bits that appears to be statistically independent and unbiased.
Relying party	An entity that relies on the certificate and the CA that issued the certificate to verify the identity of the certificate owner, and the validity of the public key, associated algorithms and any relevant parameters in the certificate, as well as the owner's possession of the corresponding private key.
RSA	A public-key algorithm that is used for key establishment and the generation and verification of digital signatures.
Scheme	A set of unambiguously specified transformations that provide a (cryptographic) service (e.g., key establishment) when properly implemented and maintained. A scheme is a higher-level

	construct than a primitive and a lower-level construct than a protocol.
Secret key	A single cryptographic key that is used with a symmetric (secret key) cryptographic algorithm and is not made public; i.e., the key is kept secret. A secret key is also called a symmetric key. The use of the term "secret" in this context does not imply a classification level, but rather implies the need to protect the key from disclosure. Compare with a private key, which is used with a public key algorithm.
Secret key (symmetric) cryptographic algorithm	See *symmetric (secret key) algorithm*.
Sensitive (information)	Sensitive, but unclassified information.
Security function	Cryptographic algorithms, together with modes of operation (if appropriate); for example, block ciphers, digital signature algorithms, asymmetric key-establishment algorithms, message authentication codes, hash functions, or random bit generators. See FIPS 140.[5]
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.
Server	A computer or device on a network that manages network resources. Examples include file servers (to store files), print servers (to manage one or more printers), network servers (to manage network traffic), and database servers (to process database queries).
Shared secret	A secret value that is computed during a key-agreement transaction and is used as input to derive a key using a key-derivation method.
Signature generation	The use of a digital signature algorithm and a private key to generate a digital signature on data.

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[5] FIPS 140, *Security Requirements for Cryptographic Modules.*

Signature verification	The use of a digital signature and a public key to verify a digital signature on data.
Source authentication	The process of providing assurance about the source of information. Sometimes called origin authentication. Compare with *Identity authentication*.
Static key pair	A long-term key pair for which the public key is often provided in a public-key certificate.
Symmetric key	A single cryptographic key that is used with a symmetric (secret key) algorithm, is uniquely associated with one or more entities and is not made public, i.e., the key is kept secret. A symmetric key is often called a secret key.
Symmetric-key (secret key) algorithm	A cryptographic algorithm that uses the same secret key for an operation and its complement (e.g., encryption and decryption). The key is kept secret and is called either a secret key or symmetric key.

1.6   Acronyms

90	AES	Advanced Encryption Standard; specified in FIPS 197.[6]
91	ANS	American National Standard.
92	ANSI	American National Standard Institute.
93	ASC	Accredited Standards Committee.
94	CA	Certification Authority.
95	CBC	Cipher Block Chaining mode; specified in SP 800-38A.[7]
96	CFB	Cipher Feedback mode; specified in SP 800-38A.
97	CKMS	Cryptographic Key Management System.
98	CP	Certificate Policy.
99	CPS	Certification Practice Statement.
100	CRL	Certificate Revocation List.
101	CTR	Counter mode; specified in SP 800-38A.
102 103	DES	Data Encryption Standard; originally specified in FIPS 46; now provided in SP 800-67.[8]
104	DH	Diffie-Hellman algorithm.
105	DNSSEC	Domain Name System Security Extensions.
106	DRBG	Deterministic Random Bit Generator; specified in SP 800-90A.[9]
107	DSA	Digital Signature Algorithm; specified in FIPS 186.[10]

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[6] FIPS 197, *Advanced Encryption Standard (AES)*.

[7] SP 800-38A, *Recommendation for Block Cipher Modes of Operation: Methods and Techniques*.

[8] SP 800-67, *Recommendation for the Triple Data Encryption Algorithm (TDEA) Block Cipher*.

[9] SP 800-90A, *Recommendation for Random Number Generation Using Deterministic Random Bit Generators*.

[10] FIPS 186, *Digital Signature Standard (DSS)*.

108	ECB	Electronic Codebook mode; specified in SP 800-38A.
109	ECDSA	Elliptic Curve Digital Signature Algorithm.
110	EMC	Electromagnetic Compatibility.
111	FCKMS	Federal Cryptographic Key Management System.
112	FIPS	Federal Information Processing Standard.
113	FISMA	Federal Information Security Management Act.
114	GCM	Galois Counter Mode; specified in SP 800-38D.[11]
115	HMAC	Keyed-Hash Message Authentication Code; specified in FIPS 198.[12]
116	IEC	International Electrotechnical Commission.
117	IEEE	Institute of Electrical and Electronics Engineers.
118	IETF	Internet Engineering Task Force.
119	EMI	Electromagnetic Interference.
120	INCITS	International Committee for Information Technology Standards.
121	IPSEC	Internet Protocol Security.
122	ISO	International Standards Organization.
123	IT	Information Technology.
124	KMAC	KECCAK Message Authentication Code; specified in SP 800-185.[13]
125	MAC	Message Authentication Code.
126	MQV	Menezes-Qu-Vanstone algorithm; specified in SP 800-56A.[14]
127	NRBG	Non-deterministic Random Bit Generator.
128	NIST	National Institute of Standards and Technology.
129	OFB	Output Feedback mode; specified in SP 800-38A.
130	OMB	Office of Management and Budget.
131	OTAR	Over-the-Air-Rekeying.
132	PKI	Public Key Infrastructure.
133	RA	Registration Authority.
134	RBG	Random Bit Generator.
135	RFC	Request for Comment.
136	RSA	A public key algorithm attributed to Rivest, Shamir and Adleman.
137	ROTs	Roots of Trust
138	SHA	Secure Hash Algorithm.
139	SP	Special Publication.
140	SSH	Secure Shell protocol.
141	TCG	Trusted Computing Group.
142	TDEA	Triple Data Encryption Algorithm; specified in SP 800-67.
143	TLS	Transport Layer Security.
144	TPM	Trusted Platform Module.

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[11] SP 800-38D, *Recommendation for Block Cipher Modes of Operation: Galois/Counter Mode (GCM) and GMAC.*

[12] FIPS 198, *Keyed-Hash Message Authentication Code (HMAC).*

[13] SP 800-185, *SHA-3 Derived Functions: cSHAKE, KMAC, TupleHash and ParallelHash.*

[14] SP 800-56A, *Recommendation for Pair-Wise Key-Establishment Schemes Using Discrete Logarithm Cryptography.*

145 **1.7   Content**

146 This document is organized into the following sections:

147   • Section 1 provides an introduction to the SP 800-175 series of publications and to
148   this document in particular, and provides a glossary of terms and a list of acronyms.

149   • Section 2 discusses the importance of standards, as well as the national and
150   international standards bodies concerned with cryptography.

151   • Section 3 introduces the **approved** algorithms used for encryption, digital signature
152   and key-establishment, and provides discussions on security strengths and
153   algorithm lifetime.

154   • Section 4 discusses the services that cryptography can provide: data confidentiality,
155   data integrity authentication, identity authentication, source authentication and
156   support for non-repudiation.

157   • Section 5 discusses the key management required for the use of cryptography,
158   providing general guidance and discussions on key-management systems, key-
159   establishment mechanisms and random bit generation.

160   • Section 6 discusses additional issues associated with the use of cryptography.

161   • Appendix A lists applicable Federal Information Processing Standards,
162   recommendations, and guidelines.

163   • Appendix B provides a list of revisions since the original publication of this
164   document.

165

166 ## 2.0   STANDARDS AND GUIDELINES

167 ### 2.1   Benefits of Standards

168 Standards define common practices, methods, and measures/metrics. Standards provide
169 solutions that have been evaluated by experts in relevant areas, reviewed by the public and
170 subsequently accepted by a wide community of users. By using standards, organizations
171 can reduce costs and protect their investments in technology.

172 Standards provide the following benefits:

173 • **Interoperability.** Products developed to a specific standard may be used to provide
174   interoperability with other products that conform to the same standard.   For
175   example, by using the same cryptographic encryption algorithm, data that was
176   encrypted using vendor A's product may be decrypted using vendor B's product.
177   The use of a common standards-based cryptographic algorithm is necessary, but
178   may not be sufficient to ensure product interoperability. Other common standards,
179   such as communications protocol standards, may also be necessary.

180   By ensuring interoperability among the products of different vendors, standards
181   permit an organization to select from various available products to find the most
182   cost-effective solution.

183 • **Security.** Standards may be used to establish a common level of security.   For
184   example, most agency managers are not cryptographic security experts, and, by
185   using an **approved** cryptographic algorithm and key length, a manager knows that
186   the algorithm has been found to be adequate for the protection of sensitive
187   government data and has been subjected to a significant period of public analysis
188   and comment.

189 • **Quality.** Standards may be used to assure the quality of a product. Standards may:

190   o Specify how a feature is to be implemented,

191   o Require self-tests to ensure that the product is still functioning correctly,
192   and

193   o Require specific documentation to assure proper implementation and
194   product-change management.

195   Many NIST standards have associated conformance tests and specify the
196   conformance requirements. The conformance tests may be administered by NIST-
197   accredited laboratories and provide validation that the NIST standard was correctly
198   implemented.

199 • **Common Form of Reference.** A NIST standard may become a common form of
200   reference to be used in testing/evaluating a vendor's product. For example, FIPS
201   140 contains security and integrity requirements for any cryptographic module
202   implementing cryptographic operations.

203 • **Cost   Savings.**   Implementations   that   comply   with   commonly   accepted
204   specifications provided by standards can save money. Without standards, users may

205   be required to become experts in every information technology (IT) product that is
206   being considered for procurement. Also, without standards, products may not
207   interoperate with different products purchased by other users. This could result in
208   a significant waste of money or in the delay of implementing an IT solution.

2.2   Federal Information Processing Standards and Special Publications

2.2.1   The Use of FIPS and SPs

211   The use of a Federal Information Processing Standard (FIPS) is *mandatory* for the Federal
212   Government whenever the type of service specified in that standard is required by a federal
213   agency for the protection of sensitive information. For example, FIPS 197 contains a
214   specific set of technical security requirements for the AES algorithm. Whenever AES is
215   used by an agency, its implementation and use must conform to FIPS 197. A FIPS is
216   **approved** by the Secretary of Commerce.

217   A NIST Special Publication (SP) is similar to a FIPS, but is not mandatory unless a
218   particular government agency (e.g., OMB) makes it so. An SP does not need the approval
219   of the Secretary of Commerce.

220   Although the requirements for the use of a FIPS and an SP are different, both types of
221   publications have been subjected to the same review process by the federal agencies and
222   the public. The approval process for a FIPS is more formal than that of an SP, and
223   subsequently takes longer for the initial approval and the approval of any subsequent
224   revisions.

225   When a federal agency requires the use of cryptography (e.g., for encryption), an **approved**
226   algorithm must be used; approval is indicated by inclusion in a FIPS or SP. For example,
227   AES (as specified in FIPS 197) is an **approved** algorithm. Whenever encryption is used
228   by a federal agency for the protection of sensitive information, an **approved** encryption
229   algorithm must be implemented and used as specified. In addition to using **approved**
230   algorithms, federal agencies are required to use only implementations of these algorithms
231   that have been validated and are included in validated cryptographic modules (see Section
232   5.4.5 for further discussion).

233   When developing a specification or the criteria for the selection of a cryptographic
234   mechanism or service, cryptographic algorithms specified in FIPS and SPs must be used,
235   when available. Some guidelines may be used to specify the functions that the algorithm
236   will perform (e.g., FIPS 199 [15] or SP 800-53 [16]). Other NIST standards specify the operation
237   and use of specific types of algorithms (e.g., AES, ECDSA) and the level of independent
238   testing required for classes of security environments (e.g., FIPS 140).

239   Appendix A contains a list of FIPS and SPs that apply to the implementation of
240   cryptography in the Federal Government. Note that when a FIPS is revised, its number is
241   commonly followed by a revision number that indicates the number of times that it has
242   been revised (e.g., "FIPS 186-5" is used to indicate the fifth revision of FIPS 186); this
243   practice is not used in the main body of this document; the reader must refer to the latest

[15] FIPS 199, *Standards for Security Categorization of Federal Information and Information Systems.*

[16] SP 800-53, *Security and Privacy Controls for Federal Information Systems and Organizations.*

244　version of the FIPS or SP that has been officially **approved** (see
245　http://csrc.nist.gov/publications/; note that this site also contains clearly marked draft
246　publications).

2.2.2　FIPS Waivers

248　In the past, a waiver was sometimes issued by an agency to indicate that the use of a FIPS
249　was not required by that agency. However, the Federal Information Security Management
250　Act (FISMA) of 2002 (P.L. 107-347) eliminated previously authorized provisions for
251　waivers from FIPS. The prohibition of waivers (except by the President) has been retained
252　in subsequent cybersecurity legislation. (See SP 800-175A for a discussion of legislative
253　mandates and executive direction.).

2.3　Other Standards Organizations

255　NIST develops standards, recommendations, and guidelines that are used by vendors who
256　are developing security products, components, and modules. These products may be
257　acquired and used by Federal Government agencies. In addition, there are other groups that
258　develop and promulgate standards. These organizations are briefly described below.

2.3.1　American National Standards Institute (ANSI) [17]

260　The American National Standards Institute (ANSI) is the administrator and coordinator of
261　the United States' private-sector voluntary standardization system. ANSI does not develop
262　American National Standards itself; rather, it facilitates the development of standards by
263　establishing consensus among qualified groups.

264　Several ANSI committees have developed standards that use cryptography, but the primary
265　committee that has developed standards for the cryptographic algorithms themselves is
266　Accredited Standards Committee (ASC) X9, which is a financial-industry committee. [18]
267　Many of the standards developed within ASC X9 have been adopted within NIST standards
268　(e.g., the Elliptic Curve Digital Signature Algorithm specified in American National
269　Standard X9.62 [19] has been adopted in FIPS 186); likewise, ASC X9 has approved the use
270　of NIST standards via a registry of approved standards from non-ASC X9 sources (e.g.,
271　AES, as specified in FIPS 197).

272　A number of ASC X9 standards have also been incorporated into the standards of other
273　standards bodies, such as the International Standards Organization (ISO) (see Section
274　2.3.4) via a Technical Advisory Group (TAG) called the International Committee on
275　Information Technology Standards (INCITS). INCITS has been responsible for assuring
276　that U.S. standards (e.g., both those developed by NIST and those developed within ASC
277　X9) are incorporated within ISO standards.

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[17] Further information is available at the ANSI web site: www.ansi.org.

[18] Further information is available at the ANSI X9 web site: x9.org.

[19] ANS X9.62, *Public Key Cryptography for the Financial Services Industry: The Elliptic Curve Digital Signature Algorithm (ECDSA)*.

2.3.2 Institute of Electrical and Electronics Engineers (IEEE) Standards Association[20]

IEEE is an international, professional association that is dedicated to advancing technological innovation and excellence. The technical objectives of the IEEE focus on advancing the theory and practice of electrical, electronics and computer engineering, and computer science. IEEE develops and disseminates voluntary, consensus-based industry standards involving leading-edge electro-technology. IEEE supports international standardization and encourages the development of globally acceptable standards.

The Institute of Electrical and Electronics Engineers Standards Association (IEEE-SA) is an organization within IEEE that develops global standards. It has more than one thousand active standards, some of which are related to cryptography.

IEEE P1363[21] is the only IEEE standard that focuses on cryptography and includes a series of standards on public-key cryptography. IEEE P1363 was developed at the same time as many of the ANSI public-key cryptographic standards that were developed in ASC X9 (see Section 2.4.1).

- The first part of the IEEE P1363 standard was published in 2000 and revised in 2004 as IEEE P1363a.[22] It includes the basic public-key cryptography schemes, such as RSA encryption, digital signatures, the Digital Signature Algorithm (DSA), and key establishment using Diffie-Hellman (DH) and Menezes-Qu-Vanstone (MQV) over finite fields and elliptic curves.

- IEEE P1363.1,[23] which was published in 2008, specifies NTRU encryption and signature schemes.

- IEEE P1363.2[24] was also published in 2008. It specifies password-authenticated key agreement and password-authenticated key retrieval schemes.

The schemes specified in IEEE P1363.1 and P1363.2 are not included in the NIST standards.

Cryptographic schemes are used in IEEE standards for different applications. One of the more notable is the IEEE 802 LAN/MAN group of standards, which are widely used computer networking standards for both wired (Ethernet) and wireless (IEEE 802.11[25]) networks. Cryptographic algorithms are used to protect wireless communications. The CCM mode for authentication and confidentiality specified in SP 800-38C[26] was adopted from IEEE 802.11. Other AES modes of operation (e.g., GCM, which is specified in SP 800-38D) are also used in IEEE 802 standards. IEEE 802 standards also use the SHA-1

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[20] Further information is available at the IEEE-SA web site: standards.ieee.org.

[21] IEEE P1363, Standard Specifications for Public-Key Cryptography.

[22] IEEE P1363a, *Standard Specifications for Public Key Cryptography - Amendment 1: Additional Techniques*.

[23] IEEE P1363.1, *Public-Key Cryptographic Techniques Based on Hard Problems over Lattices*.

[24] IEEE P1363.2, *Password-Based Public-Key Cryptography*.

[25] IEEE 802.11, *Wireless Local Area Networks*.

[26] SP 800-38C, *Recommendation for Block Cipher Modes of Operation: the CCM Mode for Authentication and Confidentiality*.

311 and SHA-2 family of hash functions specified in FIPS 180[27] and used in HMAC, as
312 specified in FIPS 198.

313 XTS, a block cipher mode of operation specified in SP 800-38E,[28] was adopted from IEEE
314 P1619[29] as SP 800-38E.

2.3.3   Internet Engineering Task Force (IETF)

316 The Internet Engineering Task Force (IETF) is an international community of network
317 designers, operators, vendors, researchers, and technologists that work on the Internet
318 architecture, and its techniques and protocols. An IETF official technical specification or
319 recommendation is called a Request for Comments (RFC).

320 The technical work of the IETF is done in its working groups, which are organized by topic
321 into several areas, such as routing, transport and security. In the security area, different
322 working groups are formed when needed to develop different security mechanisms for
323 security protocols or applications. For example,

324   1. The PKIX (Public-Key Infrastructure X.509) Working Group (PKIX-WG)
325   developed technical specifications and recommendations to support a Public Key
326   Infrastructure, based on the X.509[30] protocol, which is used to build a trust and
327   authentication services infrastructure;

328   2. The IPSEC (Internet Protocol Security) working group developed a protocol and
329   other technical recommendations for secure routing between network devices; and

330   3. The TLS (Transport Layer Security) working group has been specifying a
331   communication protocol and technical recommendations to provide security
332   services for communication between a server and a client, etc.

333 NIST-approved cryptographic algorithms, such as block cipher modes of operation, hash
334 functions, key-establishment schemes, and digital signatures are used in various IETF
335 protocols. For example, RFC 5288[31] specifies the AES Galois Counter Mode (GCM)
336 Cipher Suites for TLS, based on SP 800-38D.

337 Further information is available at the IETF web site, http://ietf.org.

2.3.4   International Organization for Standardization (ISO)[32]

339 ISO is a non-governmental, worldwide federation of national standards bodies. Its mission
340 is to develop international standards that help to make industry more efficient and effective.
341 ISO standards cover almost all aspects of technology and business, from food safety to
342 computers, and from agriculture to healthcare. Experts from all over the world develop the

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[27] FIPS 180, *Secure Hash Standard (SHS).*

[28] SP 800-38E, *Recommendation for Block Cipher Modes of Operation: the XTS-AES Mode for Confidentiality on Storage Devices.*

[29] IEEE P1619, *Standard for Cryptographic Protection of Data on Block-Oriented Storage Devices.*

[30] X.509, *Information technology - Open Systems Interconnection -The Directory: Public-key and attribute certificate frameworks*.

[31] RFC 5288, *AES Galois Counter Mode (GCM) Cipher Suites for TLS.*

[32] Further information is available at the ISO web site, http://www.iso.org.

343   standards that are required by the nation or liaison organization they represent using a
344   consensus process.

345   ISO/IEC JTC 1 is a joint technical committee of the International Organization for
346   Standardization (ISO) and the International Electrotechnical Commission (IEC). ISO/IEC
347   JTC 1 SC 27 is the subcommittee for IT security. Working group 2 (WG2) is the group
348   developing standards for cryptography and security mechanisms. It usually has more than
349   twenty active projects to develop either a revision of an existing standard or a new standard.
350   Each standard consists of multiple parts, and each part includes multiple algorithms and/or
351   mechanisms.

352   The cryptographic algorithms and schemes in FIPS and SPs are usually included in
353   ISO/IEC standards, along with many other algorithms submitted by other countries. The
354   following is a list of ISO/IEC standards that include cryptographic algorithms and schemes
355   specified in NIST standards.

356   1. ISO/IEC 9797-1, *Information technology − Security techniques − Message*
357   *Authentication Codes (MACs) -- Part 1: Mechanisms using a block cipher*.

358   2. ISO/IEC 9797-2, *Information technology − Security techniques − Message*
359   *Authentication Codes (MACs) -- Part 2: Mechanisms using a dedicated hash-*
360   *function*.

361   3. ISO/IEC 10116, *Information technology − Security techniques − Modes of*
362   *operation for an n-bit block cipher*.

363   4. ISO/IEC 10118-3, *Information technology − Security techniques − Hash-functions*
364   *-- Part 3: Dedicated hash-functions*.

365   5. ISO/IEC 11770-3, *Information technology − Security techniques − Key*
366   *management -- Part 3: Mechanisms using asymmetric techniques*.

367   6. ISO/IEC CD 11770-6, *Information technology − Security techniques − Key*
368   *management -- Part 6: Key derivation*.

369   7. ISO/IEC 14888-2, *Information technology − Security techniques − Digital*
370   *signatures with appendix -- Part 2: Integer factorization based mechanisms*.

371   8. ISO/IEC CD 14888-3, *Information technology − Security techniques − Digital*
372   *signatures with appendix -- Part 3: Discrete logarithm based mechanisms*.

373   9. ISO/IEC 18033-3, *Information technology − Security techniques − Encryption*
374   *algorithms − Part 3: Block ciphers*.

375   10. ISO/IEC 19772, *Information technology − Security techniques − Authenticated*
376   *encryption*.

2.3.5   Trusted Computing Group (TCG)

378   The Trusted Computing Group (TCG) develops and promotes a set of industry standards
379   that build upon roots of trust. Roots of Trust (RoTs) are hardware, firmware, and software
380   components that are inherently trusted to perform specific, vital security functions.
381   Because misbehavior by RoTs cannot be detected, they must be secure by design. To

382 ensure that they are reliable and resistant to tampering, RoTs are often implemented in, or
383 protected by, hardware.

384 Industry standards developed by the TCG define the capabilities of a set of fundamental
385 roots of trust, and describe how to use those roots of trust in a variety of architectures and
386 use cases. Many of the use cases supported by TCG technologies and specifications focus
387 on one or more of the following areas: 1) device identity, 2) cryptographic key or credential
388 storage, and 3) attestation of the system state.

389 Technologies supporting TCG-developed standards are deployed enterprise-class clients
390 and servers, storage devices, embedded systems, and virtualized devices. Families of
391 relevant TCG standards and specifications include:

392 • Trusted Platform Modules (TPMs): A TPM is a cryptographic module that can,
393   among other capabilities, establish device identity in a platform, provide secure
394   storage for keys and credentials, and support the measurement and reporting of the
395   system state. The TPM 2.0 Library Specification provides the general architecture
396   and command set for TPMs, with platform-specific specifications detailing how a
397   TPM can be implemented in particular classes of systems. ISO/IEC JTC 1 has
398   approved the TPM Library Specification as ISO/IEC 11889:2015 Parts 1-4.[33]

399 • Trusted Network Connect (TNC): The TCG's TNC Working Group defines
400   specifications that allow network administrators to enforce policies regarding
401   endpoint integrity on devices connected to a network. These specifications were the
402   basis for much of the work in the IETF's Network Endpoint Assessment (NEA)
403   working group, and are highly complementary to the on-going work in the IETF
404   Security Automation and Continuous Monitoring (SACM) working group.

405 • Storage: The TCG's Storage Working Group defines specifications that enable
406   standards-based mechanisms to protect data on storage devices, and manage these
407   devices and capabilities. The TCG's storage specifications break out from a
408   common core specification into two Security Subsystem Classes (SSCs): the Opal
409   SSC, which is intended for client devices (e.g., tablets, notebooks and desktops),
410   and the Enterprise SSC, which is intended for high-performance storage systems
411   (e.g., servers).

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[33] ISO/IEC 11889:2015 Parts 1-4, *Trusted Platform Module; Part 1: Architecture, Part 2: Structures, Part 3: Commands, and Part 4: Supporting Routines*.

3.0   CRYPTOGRAPHIC ALGORITHMS

This document describes three types of cryptographic algorithms: cryptographic hash functions, symmetric-key algorithms and asymmetric-key algorithms, which are discussed in Sections 3.1, 3.2 and 3.3, respectively. Other topics to be introduced in this section include the concept of algorithm security strength and algorithm lifetime (see Sections 3.4 and 3.5, respectively).

3.1   Cryptographic Hash Functions

A hash function (also called a hash algorithm) is a cryptographic primitive algorithm that produces a condensed representation of its input (e.g., a message). A hash function takes an input of arbitrary length and outputs a value with a predetermined length. Common names for the output of a hash function include *hash value* and *message digest*.

A cryptographic hash function is a one-way function that is extremely difficult to invert. That is, it is not practical to reverse the process from the hash value back to the input.

Figure 1 depicts the process of generating and verifying a hash value.
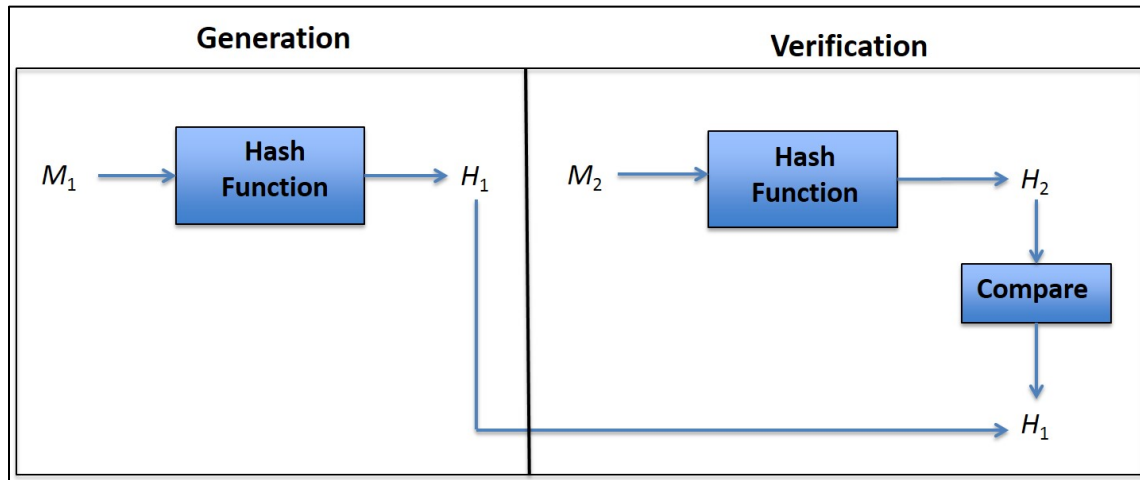
Figure 1: Hash Function Generation and Verification

A hash function is used as follows:

- Hash Generation:
    1. Hash value (H_1) is generated on data (M_1) using the hash function.
    2. M_1 and H_1 are then saved or transmitted.
- Hash Verification:
    1. Hash value (H_2) is generated on the received or retrieved data (M_2) using the same hash function that generated H_1.
    2. H_1 and H_2 are compared. If $H_1 = H_2$, then it can be assumed that M_1 has not changed during storage or transmission.

437 The above description is for the simplest use of a hash function. Hash functions are usually
438 used in higher-level algorithms, including:

439 • Keyed-hash message authentication code algorithms (Sections 3.2.2 and 4.2.2.2),

440 • Digital signature algorithms (Section 4.2.3),

441 • Key derivation functions (e.g., for key establishment) (Section 5.3.2), and

442 • Random bit generators (Section 4.4).

443 **Approved** hash functions for Federal Government use are specified in FIPS 180, FIPS
444 202 [34] and SP 800-185.

445 • FIPS 180 specifies the SHA-1 hash function and the SHA-2 family of hash
446 funcitons: SHA-224, SHA-256, SHA-384, SHA-512, SHA-512/224 and SHA-
447 512/256. Additional guidance for the use of these hash functions is provided in SP
448 800-106 [35] and SP 800-107. [36]

449 Note that attacks on SHA-1 have indicated that SHA-1 provides less security than
450 originally thought when generating digital signatures (see Section 4.2.3);
451 consequently, SHA-1 is now disallowed for that purpose. However, SHA-1 may
452 continue to be used for most other hash-function applications, including the
453 verification of digital signatures previously signed using SHA-1 as the hash
454 function (see SP 800-131A [37]).

455 • FIPS 202 specifies the SHA-3 family of hash functions: SHA3-224, SHA3-256,
456 SHA3-384 and SHA3-512. This FIPS also specifies two extendable-output
457 functions (SHAKE128 and SHAKE256), which are not, in themselves, considered
458 to be hash functions.

459 The numbers in each hash function name are used to indicate the length of the output of
460 that hash function (e.g., SHA-1 produces 160 bit outputs, while SHA-XXX and SHA3-
461 XXX produce outputs of a length indicated by XXX.

462 • SP 800-185 specifies the TupleHash and ParallelHash functions. Both hash
463 functions can produce variable-length output. TupleHash is designed to hash tuples
464 of input.

3.2   Symmetric-Key Algorithms

466 Symmetric-key algorithms (sometimes called secret-key algorithms) use a single key to
467 both apply cryptographic protection and to remove or check the protection; i.e., the same
468 key is used for a cryptographic operation and its inverse. For example, the key used to
469 encrypt data (i.e., apply protection) is also used to decrypt the encrypted data (i.e., remove
470 the protection); in the case of encryption, the original data is called the plaintext, while the

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[34] FIPS 202, *SHA-3 Standard: Permutation-Based Hash and Extendable Output Functions*.

[35] SP 800-106, *Randomized Hashing for Digital Signatures*.

[36] SP 800-107, *Recommendations for Applications Using Approved Hash Algorithms*.

[37] SP 800-131A, *Transitions: Recommendation for Transitioning the Use of Cryptographic Algorithms and Key Lengths*.

471 encrypted form of the data is called the ciphertext. The key must be kept secret if the data
472 is to remain protected.

473 Several classes of symmetric-key algorithms have been approved: those based on block
474 cipher algorithms (e.g., AES) and those based on the use of hash functions (e.g., a keyed-
475 hash message authentication code based on SHA-1).

476 Symmetric-key algorithms are used for:

477   • Encryption to provide data confidentiality (see Section 4.1),

478   • Authentication to provide assurance of data integrity and the source of the data
479   (see Section 4.2),

480   • Key derivation (see Section 5.3.2),

481   • Key wrapping (see Section 5.3.5), and

482   • Random bit generation (see Section 4.4).

483 When using a symmetric-key algorithm, a unique key needs to be generated for each
484 cryptographic relationship[38] and for each purpose (e.g., encryption, data integrity
485 authentication and key wrapping). Technically, the same key can be used for multiple
486 purposes when the same algorithm is used, but this is usually ill-advised, as the use of the
487 same key for two different cryptographic processes (e.g., HMAC and key derivation using
488 the same hash function) may weaken the security provided by one or both of the processes.
489 However, exceptions to this rule have been approved (see Section 4.3).

490 As an example of the number of keys required for the use of symmetric-key algorithms,
491 suppose that there are four entities (A, B, C, and D) that need to communicate using
492 encryption, with each pair of entities using a different encryption key. There are six
493 possible pair-wise relationships (A-B, A-C, A-D, B-C, B-D, and C-D), so, at least six keys
494 are required.[39] If, instead, there are 1000 entities that wish to communicate with each other,
495 there are 499,500 possible pair-wise relationships, and at least one unique key would be
496 required for each relationship. If more than one algorithm, key length or purpose is to be
497 supported (e.g., both encryption and key wrapping), then additional keys will be needed.
498 Each entity must keep all its symmetric keys secret and protect their integrity. The need for
499 a large number of keying relationships is a significant problem; methods for mitigating this
500 problem are discussed in Section 5.

501 Several symmetric-key algorithms have been **approved** by NIST for the protection of
502 sensitive data. However, some of these algorithms are no longer approved for applying
503 cryptographic protection (e.g., encryption), but may continue to be used for processing
504 already-protected information (e.g., decryption), providing that the risk of doing so is
505 acceptable (e.g., there is reason to believe that a key was not compromised). See SP 800-

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[38] A cryptographic relationship exists when two or more parties can communicate using the same key and
algorithm. A relationship may be one-to-one or one-to-many (e.g., broadcast).

[39] Although only six cryptographic relationships are used in the example, different keys may be required by
some protocols for each communication direction, i.e., a different key may be required for communications
sent from A to B than is used for communications sent from B to A.

506   57, Part 1 and SP 800-131A for more information about the acceptability of using the
507   different cryptographic algorithms.

3.2.1   Block Cipher Algorithms

509   A block cipher algorithm is used with a single key in an **approved** mode of operation to
510   both apply cryptographic protection (e.g., encrypt) and to subsequently process the
511   protected information (e.g., decrypt). Several block cipher algorithms have been approved
512   by NIST as cryptographic primitives, some of which are no longer approved for applying
513   cryptographic protection. However, they may still be needed for processing information
514   that was previously protected (e.g., they may be needed for decrypting previously
515   encrypted information).

516   The block cipher algorithms are discussed in Sections 3.2.1.1 through 3.2.1.4. **Approved**
517   modes of operation are discussed in Section 3.2.1.5.

3.2.1.1   Data Encryption Standard (DES)

519   The Data Encryption Standard (DES) was approved in July 1977, and was the first NIST-
520   **approved** cryptographic algorithm. It was reaffirmed several times, but due to advances in
521   computer power and speeds, the strength of the DES algorithm is no longer sufficient to
522   adequately protect Federal Government information. Therefore, DES was withdrawn as an
523   **approved** algorithm in 2005 (i.e., the use of DES is no longer approved for encryption or
524   otherwise applying cryptographic protection). However, the DES "cryptographic engine"
525   continues to be used as a component function of TDEA (see the next section).

3.2.1.2   Triple Data Encryption Algorithm (TDEA)

527   The Triple Data Encryption Algorithm (TDEA), also known as Triple DES, uses the DES
528   cryptographic engine to transform data in three operations (see SP 800-67). TDEA encrypts
529   data in blocks of 64 bits using three keys that define a key bundle. Two variations of TDEA
530   have been defined: two-key TDEA (2TDEA), in which the first and third keys are identical,
531   and three-key TDEA (3TDEA), in which the three keys are all different (i.e., distinct).

532   A number of attacks on TDEA have been published that indicate that the security life of
533   TDEA is nearing its conclusion, so NIST announced plans[40] to discontinue approval for
534   the use of TDEA for federal applications. A schedule has been published in SP 800-131A.

535   The use of 2TDEA is **disallowed** for applying cryptographic protection (e.g., for
536   encrypting plaintext data). However, 2TDEA may continue to be used for processing
537   already-protected information (e.g., for decrypting ciphertext data), but the user must
538   accept some risk that increases over time. For example, if the data was encrypted and
539   transmitted over public networks when the algorithm was still considered secure, the
540   ciphertext may have been captured (by an adversary) at that time and later decrypted by
541   that adversary when the algorithm was no longer considered secure; thus, the
542   confidentiality of the data would no longer be assured.

543   The use of 3TDEA for applying cryptographic protection (e.g., encrypting) has been
544   **deprecated**, i.e., the user must accept some risk when using the algorithm to apply

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[40] See https://csrc.nist.gov/news/2017/update-to-current-use-and-deprecation-of-tdea.

545 protection; in addition, SP 800-67 includes a restriction on the amount of data that can be
546 protected with a single three-key bundle. Federal applications **shall** only use three distinct
547 keys whenever using TDEA for applying cryptographic protection. After December 31,
548 2023, 3TDEA will be **disallowed** for applying cryptographic protection but may continue
549 to be used for processing already-protected information, again with the stipulation that the
550 user must accept some security risk.

3.2.1.3   SKIPJACK

552 SKIPJACK is referenced in FIPS 185[41] and specified in a classified document. SKIPJACK
553 is no longer considered adequate for the protection of federal information and has been
554 withdrawn as a FIPS. The use of SKIPJACK for applying cryptographic protection (e.g.,
555 encryption) is **disallowed**, although it is permissible to use the algorithm for decrypting
556 information.

3.2.1.4   Advanced Encryption Standard (AES)

558 The Advanced Encryption Standard (AES) was developed as a replacement for DES and
559 TDEA and is the preferred block cipher algorithm for new products. AES is specified in
560 FIPS 197. AES operates on 128-bit blocks of data, using 128-, 192- or 256-bit keys. The
561 nomenclature for AES for the different key sizes is AES-x, where x is the key size (i.e.,
562 AES-128, AES-192 and AES-256). The use of AES is acceptable (i.e., considered secure)
563 for all AES applications, although the key size may be a factor when using AES (see
564 Section 3.4)

3.2.1.5   Modes of Operation

566 With a symmetric-key block cipher algorithm, the same input block will always produce
567 the same output block when the same key is used. If the multiple blocks in a typical
568 message are encrypted separately, an adversary can easily substitute individual blocks,
569 possibly without detection. Furthermore, certain kinds of data patterns in the plaintext, such
570 as repeated blocks, would be apparent in the ciphertext. To counteract these properties,
571 modes of operation have been specified for using a block cipher algorithm.

572 These modes combine the cryptographic primitive algorithm with a symmetric key and
573 variable starting values (commonly known as initialization vectors) to provide some
574 cryptographic service (e.g., the encryption of a message or the generation of a message
575 authentication code). **Approved** modes for block cipher algorithms have been specified in
576 the SP 800-38 series of publications and include modes for:

577 • Encryption, as specified in SP 800-38A, SP 800-38E and SP 800-38G[42] (see
578   Section 4.1),

579 • Authentication, as specified in SP 800-38B[43] (see Section 4.2.2.1),

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[41] FIPS 185, *Escrowed Encryption Standard*.

[42] SP 800-38G, *Recommendation for Block Cipher Modes of Operation: Methods for Format-Preserving
    Encryption.*

[43] SP 800-38B, *Recommendation for Block Cipher Modes of Operation: the CMAC Mode for
Authentication.*

580 • Authenticated encryption, as specified in SP 800-38C and SP 800-38D (see Section
581   4.3), and

582 • Key wrapping, as specified in SP 800-38F (see Section 5.3.5).

583 **3.2.2 Hash-based Symmetric-key Algorithms**

584 A symmetric-key algorithm based on the use of a hash function has been specified in FIPS
585 198 for generating a message authentication code (MAC). This algorithm, known as
586 HMAC, has been **approved** for use with any **approved** hash function specified in FIPS
587 180 or FIPS 202. Guidance on the use of the hash functions specified in FIPS 180 for
588 HMAC is provided in SP 800-107.

589 SP 800-185 specifies an additional MAC algorithm, known as KMAC, which is based on
590 the extendable output funciton specified in FIPS 202. KMAC has two variants: KMAC128
591 and KMAC256.

592 **3.3   Asymmetric-Key Algorithms**

593 Asymmetric-key algorithms (often called public-key algorithms) use a pair of keys (i.e., a
594 key pair): a public key and a private key that are mathematically related to each other. The
595 public key may be made public without reducing the security of the process, but the private
596 key must remain secret if the cryptographic protection is to remain effective. Even though
597 there is a relationship between the two keys, the private key cannot efficiently be
598 determined based on knowledge of the public key.

599 One of the keys of the key pair is used to apply cryptographic protection, and the other key
600 is used to remove or verify that protection. The key to use depends on the algorithm used
601 and the service to be provided. For example, a digital signature is computed using a private
602 key, and the signature is verified using the public key (i.e., the protection is applied using
603 the private key and verified using the corresponding public key). For those asymmetric
604 algorithms also capable of encryption,[44] the encryption is performed using the public key,
605 and the decryption is performed using the private key (i.e., the protection is applied using
606 the public key and removed using the private key).

607 Asymmetric-key algorithms are used, for example,

608 1. To provide identity, integrity and source authentication services in the form of
609   digital signatures (see Sections 3.3.1 and 4.2.3); and

610 2. To establish cryptographic keying material using key-agreement and key-transport
611   algorithms (see Sections 3.3.2 and 5.3)).

612 These algorithms tend to be much slower than symmetric-key algorithms, so are not used
613 to process large amounts of data. However, when used for key establishment (see Section
614 5), there are methods that combine the use of symmetric and asymmetric algorithms to
615 reduce the number of keys required for establishing cryptographic relationships.

---

[44] Not all public-key algorithms are capable of multiple functions, e.g., both encryption and decryption, and
the generation and verification of digital signatures.

616   Key pairs for asymmetric-key algorithms should be generated for each purpose (e.g., one
617   key pair for generating and verifying digital signatures, and a different key pair for key
618   establishment). Technically, it is sometimes possible to use the same key pair for more than
619   one purpose, but this is ill-advised, as the use of the same key pair for two different
620   cryptographic purposes (e.g., digital signatures and key establishment) may weaken the
621   security provided by one or both of the processes.

622   The use of asymmetric-key algorithms requires the establishment of fewer initial keys than
623   the use of symmetric-key algorithms. As an example, suppose that an entity wants to
624   generate digital signatures and participate in a key-establishment process using its own key
625   pair;[45] a key pair needs to be generated for each purpose. If there are six entities that intend
626   to both generate digital signatures and participate in the key-establishment process, then
627   six key pairs are needed for digital signature generation, and another six key pairs are
628   needed for key establishment, for a total of twelve key pairs. For 1000 entities, 1000 key
629   pairs of each would be needed for each purpose, for a total of 2000 key pairs. A unique key
630   pair does not need to be generated for each relationship; recall that for symmetric-key
631   algorithms, a unique key does need to be generated for each relationship (see Section 3.2).
632   If multiple public-key algorithms or key lengths are to be used for either process, then
633   additional key pairs will be required.

634   The private key is retained and used by the entity who "owns" the key pair; it must be kept
635   secret and its integrity protected. The public key is usually distributed to other entities and
636   requires integrity protection but not confidentiality protection; distribution is often
637   accomplished by using a public-key certificate, as discussed in Section 5.2.3. When a
638   public-key certificate is used, the certificate provides the integrity protection for the public
639   key, so the burden of key protection by each entity is limited to only those private keys
640   owned by the entity.

641   Some asymmetric-key algorithms use domain parameters, which are additional values
642   necessary for the use of the cryptographic algorithm. These values are mathematically
643   related to each other and to the keys with which they will be used. Domain parameters are
644   usually public and are used by a community of users for a substantial period of time. These
645   domain parameters are either contained within or referenced by a certificate containing a
646   public key.

647   The secure use of asymmetric-key algorithms is dependent on users obtaining certain
648   assurances:

649   •   Assurance of domain-parameter validity (for those algorithms requiring domain
650   parameters) provides confidence that the domain parameters are mathematically
651   correct,

652   •   Assurance of public-key validity provides confidence that the public key appears
653   to be a suitable key, and

---

[45] Note that some key-establishment schemes do not require that all parties have key pairs, so some parties
      will not need a key pair for key establishment.

654   • Assurance of private-key possession provides confidence that the entity that is
655   supposedly the owner of the private key really has the key.

656   **Important note:** When large-scale quantum computers become available, they will
657   threaten the security of the **approved** asymmetric-key algorithms. In particular, the digital
658   signature schemes, key-agreement schemes using Diffie-Hellman and MQV,[46] and the
659   key-agreement and key-transport schemes using RSA may need to be replaced with secure
660   quantum-resistant (or "post-quantum") counterparts. At the time that this revision of SP
661   800-175B was published, NIST was undergoing a process to select post-quantum
662   cryptographic algorithms for standardization. This process is a multi-year project; when
663   these new standards are available, this document will be updated appropriately. See
664   https://csrc.nist.gov/Topics/Security-and-Privacy/cryptography/post-quantum-
665   cryptography for the status of this effort.

3.3.1   Digital Signature Algorithms

667   Digital signatures are used to provide identity authentication, integrity authentication,
668   source authentication, and support for non-repudiation. Digital signatures are used in
669   conjunction with hash functions and are computed on data of any length (up to a limit that
670   is determined by the hash function). FIPS 186 specifies algorithms that are **approved** for
671   the computation of digital signatures.[47] It specifies the Digital Signature Algorithm (DSA),
672   the Elliptic Curve Digital Signature Algorithm (ECDSA), and adopts the RSA algorithm,
673   as specified in RFC 8017[48] and PKCS 1[49] (version 1.5 and higher), and the Edwards-Curve
674   Digital Signature Algorithm (EdDSA) specified in RFC 8032.[50]

675   FIPS 186 also specifies several **approved** key sizes for each of these algorithms and
676   includes methods for generating the algorithm's key pairs and many other parameters
677   needed for digital signature generation and verification. However, SP 800-186 (a new
678   publication) contains the recommended elliptic curves to be used with ECDSA and
679   EdDSA.

680   Digital signature generation **shall** be performed using keys that meet or exceed the key
681   sizes specified in FIPS 186 and using key pairs that are generated in accordance with FIPS
682   186. Smaller key sizes **shall only** be used to verify signatures that were generated using
683   those smaller keys. See SP 800-131A. (Older systems (legacy systems) used smaller key
684   sizes than those currently approved in FIPS 186.)

3.3.1.1   DSA

686   The Digital Signature Algorithm (DSA) is **approved** and specified in FIPS 186. This
687   algorithm is used to generate and verify digital signatures using finite-fields. FIPS 186
688   defines methods for generating DSA domain parameters and key pairs, and specifies the

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[46] Both finite field and elliptic curve versions.

[47] Two general types of digital signature methods are discussed in literature: digital signatures with appendix,
and digital signatures with message recovery. FIPS 186 specifies algorithms for digital signatures with
appendix and is the digital signature method that is discussed in this Recommendation.

[48] RFC 8017, *RSA Cryptography Specifications Version 2.2.*

[49] PKCS 1, *RSA Cryptographic Standard 1.*

[50] RFC 8032, *Edwards-Curve Digital Signature Algorithm (EdDSA).*

689 key lengths to be used for secure interoperability and the algorithms to be used for digital-
690 signature generation and verification.

3.3.1.2   ECDSA

692 The Elliptic Curve Digital Signature Algorithm (ECDSA) is **approved** and specified in
693 FIPS 186. The basic signature and verification algorithms are the same as those used for
694 DSA, except that the mathematics is based on the use of elliptic curves, rather than finite
695 fields. FIPS 186 provides guidance for the use of ECDSA within the Federal Government,
696 and SP 800-186 contains the elliptic curves to be used with ECDSA. An advantage of using
697 ECDSA instead of DSA and RSA is that the key lengths are considerably shorter, requiring
698 less storage space and transmission bandwidth, and the execution of the algorithm is
699 generally faster than DSA and RSA

700 FIPS186 includes specifications for the generation of the ECDSA domain parameters and
701 key pairs, as well as the algorithms for digital signature generation and verification; defines
702 the key lengths to be used for secure interoperability; and provides additional guidance on
703 the use of random bit generators to generate the key pairs.

3.3.1.3   EdDSA

705 EdDSA is adopted in FIPS 186 and described in RFC 8032, which includes recommended
706 parameters for the Ed25519 and Ed448 curves provided in the RFC. These curves are also
707 included in SP 800-186. While ECDSA (and DSA) signatures require the use of a random
708 (unique) value for the generation of each signature, EdDSA signatures are deterministic:
709 the unique value is computed using the private key and the message to be signed (i.e., a
710 random bit generator is not required to generate this value, thus being acceptable for
711 implementations that do not include a random bit generator).

3.3.1.4   RSA

713 The RSA algorithm is **approved** for the generation and verification of digital signatures in
714 FIPS 186 and specified in PKCS 1 and RFC 8017. FIPS 186 includes restrictions on the
715 use of RSA to generate digital signatures, methods to generate RSA key pairs, and defines
716 the key lengths to be used for secure interoperability. Additional discussions of RSA key
717 pair generation are included in SP 800-56B.[51]

3.3.2   Key-Establishment Schemes

719 Asymmetric key-establishment schemes are used to set up keys to be used between
720 communicating entities. A scheme is a set of transformations (i.e., cryptographic
721 operations) that provide a cryptographic service – a key-establishment service, in this case;
722 a scheme is used in a protocol that actually performs the communication needed for the
723 key-establishment process.

724 Two classes of asymmetric schemes have been **approved** that are based on hard
725 mathematical problems: discrete-log-based schemes and integer factorization schemes.

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[51] SP 800-56B, *Recommendation for Pair-Wise Key-Establishment Schemes Using Integer Factorization
      Cryptography.*

3.3.2.1   Diffie-Hellman and MQV

SP 800-56A specifies key-establishment schemes that use discrete-logarithm-based algorithms. These schemes are specified using either finite-field math (the form of math that most of us use) or elliptic curve math.

Two algorithms have been approved for key agreement: Diffie-Hellman (DH) and MQV.[52] The use of these algorithms for key agreement is specified in SP 800-56A and discussed in Section 5.3.3.

For finite-field DH and MQV, SP 800-56A specifies that the domain parameters be generated in the same manner as the domain parameters for DSA (see FIPS 186) or be selected from one of the domain parameter groups listed in SP 800-56A; these groups have been specified in RFC 3526[53] and RFC 7919.[54] Key pairs are generated in the same manner as for DSA (see FIPS 186).

For elliptic-curve DH and MQV, methods for generating key pairs are specified in FIPS 186 using the same methods used to generate ECDSA key pairs. Recommended elliptic curves for DH and MQV key-establishment are provided in SP 800-186, along with specifications for generating new curves.

3.3.2.2   RSA

RSA can be used for key establishment, as well as for the generation and verification of digital signatures. Its use for key establishment is specified in SP 800-56B. that publication specifies **approved** methods for both key agreement and key transport (see Section 5.3 for further information on key establishment, key agreement and key transport).

Since RSA can be used for both key establishment and the generation of digital signatures, it is important that the same keys not be used for both purposes (see Section 5.2 of SP 800-57, Part 1 for a discussion on key usage).

3.4   Algorithm Security Strength

The security strength of a cryptographic algorithm is measured by an attacker's difficulty in breaking the algorithm. Breaking a cryptographic algorithm can be defined as defeating some aspect of the protection that the algorithm is intended to provide. For example, a block-cipher encryption algorithm that is used to protect the confidentiality of data is broken if, with an acceptable amount of work, it is possible to determine the value of its key or to recover the plaintext from the ciphertext without knowledge of the key.

SP 800-57, Part 1 provides the current estimates for the security strengths that can be provided by the **approved** cryptographic algorithms; these strengths have been determined with respect to specific key lengths.

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[52] Menezes–Qu–Vanstone.

[53] RFC 3526, *More Modular Exponential (MODP) Diffie-Hellman groups for Internet Key Exchange (IKE)*.

[54] RFC 7919, *Negotiated Finite Field Diffie-Hellman Ephemeral Parameters for Transport Layer Security (TLS)*.

760   The **approved** security strengths for federal applications are 112, 128, 192 and 256 bits.
761   Note that a security strength of 80 bits was previously approved as well. Since it is no
762   longer considered as providing adequate protection, the use of algorithms and keys
763   providing a security strength of 80 bits are **no longer approved** for applying cryptographic
764   protection (e.g., encrypting data). However, algorithms and keys providing 80 bits of
765   strength can be used for processing data that was previously protected at that strength (e.g.,
766   for decryption), but some risk must be accepted.

767   Appropriate algorithms, key lengths, and key generation and handling methods need to be
768   used to actually support those security strengths, and are further discussed in Section 5.1.4.

3.5   Algorithm Lifetime

770   Over time, algorithms may be successfully attacked so that the algorithm no longer
771   provides the desired protection; DES and TDEA are examples of such algorithms (see
772   Sections 3.2.1.1 and 3.2.1.2, respectively). The attack could be on the algorithm itself, or
773   could be on the algorithm with a specific key length. In the latter case, the use of a longer
774   key for some algorithms[55] may prevent a successful attack, or at least delay it for a period
775   of time.

776   When selecting the algorithms and key lengths to be used for an application, the length of
777   time for which the data needs to be protected should be taken into account so that a suitable
778   algorithm and key length is used. SP 800-57, Part 1 provides a current estimate of the time
779   frames during which the **approved** algorithms and key lengths are considered to be secure.
780   The algorithms and key lengths used for cryptographic protection need to fall within the
781   estimated time frame. However, these estimates are just that – estimates. It is possible that
782   an advance in technology (e.g., the use of quantum computers and algorithms) or
783   cryptanalysis could occur prior to the end date of that time frame. It is often the case that
784   these advances are initially impractical or limited in their threat. It is recommended that an
785   organization have a transition strategy for addressing this problem if it occurs, including
786   assessing the risk for the compromise of the organization's data, and transitioning to a new
787   algorithm or key length if appropriate.

788

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[55] But not DES or TDEA.

789

4.0   CRYPTOGRAPHIC SERVICES

791   All sensitive information requires integrity protection, and confidentiality protection may
792   be required as well. This section discusses the cryptographic services that can be provided
793   for the protection of sensitive data other than keys. These services include data
794   confidentiality, data integrity authentication, identity authentication, source authentication
795   and support for non-repudiation. The protection and management of the keys used while
796   providing these cryptographic services are discussed in Section 5.

797   Ideally, cryptographic services would be provided using as few algorithms as possible. For
798   example, AES could be used to provide confidentiality (Section 4.1), data integrity
799   authentication (Section 4.2), key wrapping (Section 5.3.5) and as the basis for a random bit
800   generator (see Section 4.4). However, this may not be as practical as it first appears, as
801   other algorithms may also be available that are needed for different applications and that
802   provide other security properties.

4.1   Data Confidentiality

804   Encryption is used to provide confidentiality for data. The unprotected form of the data is
805   called plaintext. Encryption transforms the plaintext data into ciphertext, and ciphertext
806   can be transformed back into plaintext using decryption. Data encryption and decryption
807   are generally provided using symmetric-key block cipher algorithms. AES is **approved** for
808   data encryption using all three key sizes (see Section 3.2.1.4). While the use of three-key
809   TDEA is still allowed for encryption, its use has been deprecated (see Section 3.2.1.2 and
810   SP 800-131A).

811   Decryption of the ciphertext is performed using the algorithm and key that were used to
812   encrypt the plaintext. Unauthorized recipients of the ciphertext who know the
813   cryptographic algorithm but do not have the correct key should not be able to decrypt the
814   ciphertext. However, anyone who has the key and the cryptographic algorithm can easily
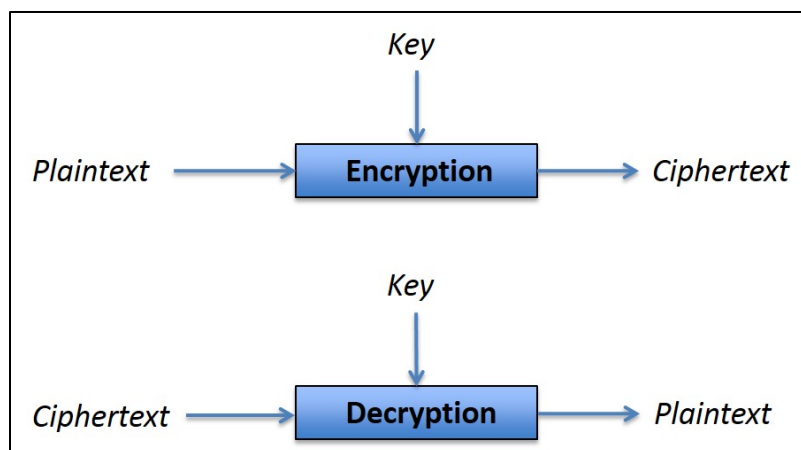815   decrypt the ciphertext and obtain the original plaintext.

816

Figure 2: Encryption and Decryption

818 Figure 2 depicts the encryption and decryption processes. The plaintext and a key are used
819 by the encryption process to produce the ciphertext. To decrypt, the ciphertext and the same
820 key are used by the decryption process to recover the plaintext data.

821 Note that asymmetric-key algorithms could also be used to encrypt and decrypt data, but
822 because these algorithms are slow in comparison to block cipher algorithms, they are not
823 normally used to encrypt and decrypt general data; they can, however, be used to protect
824 keys, as discussed in Section 5.

825 As discussed in Section 3.2.1.5, data encryption is performed using a block cipher
826 algorithm and a mode of operation. The **approved** modes of operation for encryption are
827 specified in:

828 • SP 800-38A for AES and TDEA: the Electronic Codebook (ECB), Cipher Block
829   Chaining (CBC), Cipher Feedback (CFB), Counter (CTR), and Output Feedback
830   (OFB) modes,

831 • SP 800-38E for AES: the XTS-AES mode (for protecting the confidentiality of
832   data on storage devices only), and

833 • SP 800-38G for AES: the FF1 and FF3 modes for Format Preserving Encryption
834   (FPE).

835 Additional modes that provide both confidentiality and authentication (as discussed in
836 Section 4.2) are discussed in Section 4.3.

837 4.2   Data Integrity, Identity Authentication and Source Authentication

838 Data integrity (often referred to as simply *integrity*) is concerned with whether or not data
839 has changed between two specified times (e.g., between the time when the data was created,
840 stored and/or transmitted, and the time when it was retrieved and/or received). While data
841 integrity cannot be guaranteed, the use of data integrity codes provides a means to detect
842 changes with a high probability. A data integrity code is computed on data when it is
843 created, before storage or before transmission, and computed again when the data is
844 retrieved or received. Verification that these computations agree provides a measure of
845 assurance of data integrity. In cryptographic literature, this process is called *message* (or
846 data) *authentication*, and the integrity code is often a MAC or digital signature.

847 Identity authentication (often referred to as simply *authentication*) is used to provide
848 assurance of the identity of an entity interacting with a system. The authentication process
849 usually requires that the entity produce some proof of its identity (e.g., using a token,
850 fingerprint, PIN or some combination thereof) before access to some data or resource can
851 be granted.

852 Source authentication is a process used to provide assurance of the source of information
853 that is transmitted or stored. Depending on the method used, source authentication could

854   also support non-repudiation, i.e., whether a third party (e.g., a legal entity) can be
855   convinced about who was the source of the information.[56]

856   Cryptography can be used to provide these services, but the same algorithm may not
857   provide all of them. Hash functions, as discussed in Section 4.2.1, can be used to provide
858   some assurance of data integrity. Message Authentication Code (MAC) algorithms, as
859   discussed in Section 4.2.2, can provide both data integrity and source authentication
860   services. Digital signature algorithms can be used to provide data integrity, identity
861   authentication and source authentication services, as well as supporting non-repudiation,
862   but at a higher performance cost (see Section 4.2.3).

4.2.1   Hash Functions

864   A hash function is used to generate a hash value that can provide some assurance of the
865   integrity of the data over which the hash value is generated. However, if a hash function is
866   used alone (e.g., without the use of a secret key, as is required for HMAC, or in conjunction
867   with the generation of digital signatures), there is no assurance that the data has not been
868   altered by an adversary and a new hash value computed. Therefore, the use of a hash
869   function alone for providing integrity protection is not recommended unless there is a very
870   low risk of this scenario (e.g., when data is provided by a trusted source, and the hash value
871   is used only to determine changes that may occur because of a degraded transmission
872   medium).

4.2.2   Message Authentication Code Algorithms

874   A Message Authentication Code algorithm and a cryptographic key are used to generate a
875   message authentication code (MAC) that can be used to provide assurance of data integrity
876   and source authentication. A MAC is a cryptographic checksum on the data that can
877   provide assurance that the data has not changed or been altered since it was either saved or
878   transmitted. A MAC is generated on data by one entity (say, entity A), and the integrity of
879   the data can be verified by any entity that knows the key used to generate the MAC. If the
880   data is stored with its MAC, and the key is known by entities A, B and C, then either A, B
881   or C can retrieve the data and MAC from storage and verify its integrity (i.e., verify that
882   the data has not been modified while in storage).

883   If entity A sends the data and MAC to another entity that knows the key (say, entity B), the
884   receiver (B) can verify that the data has not been modified during transmission; if only A
885   and B know the key, then entity B (the receiver) also knows that only entity A can have
886   sent the data (i.e., entity A is the source of the data). However, if the data and MAC are
887   sent to more than one entity (i.e., multiple receivers know the key, say entities B and C),
888   each receiver can verify the integrity of the received data, but assurance of the source
889   cannot be obtained, e.g., from entity B's perspective as a receiver, either entity A or entity

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[56] A real determination of non-repudiation is a legal decision with many aspects to be considered.
Cryptographic mechanisms can only be used as one element in this decision (i.e., a digital signature can
only be used to support a non-repudiation decision).

890   B could be the source, since both know the key. Note that this may be acceptable for some
891   applications.

892   MACs are used to detect data modifications that occur between the initial generation of the
893   MAC and the verification of the received or retrieved MAC. They do not detect errors that
894   occur before the MAC is originally generated. The use of MACs to provide data integrity
895   and source authentication depends on limiting knowledge of the secret key to only those
896   parties generating the MAC and those intended to retrieve or receive it. Since a MAC key
897   is shared among a community of users (e.g., two or more parties), only those parties sharing
898   the key can compute a correct MAC on given data.

899
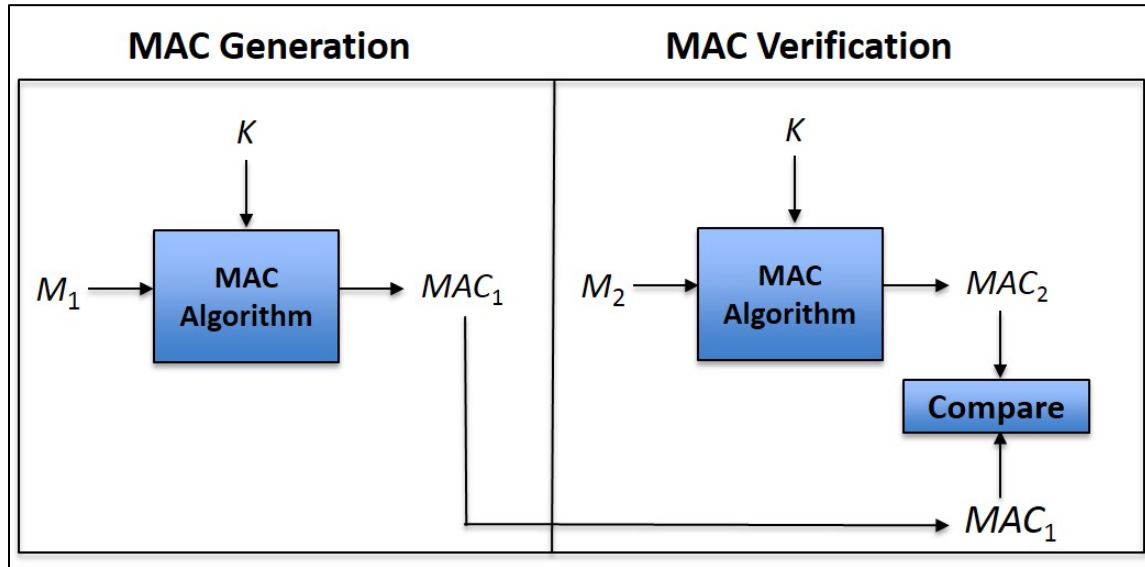
900   **Figure 3: Message Authentication and Verification**

901   Figure 3 depicts the use of MACs:

902   •   A MAC (MAC_1) is computed on data (M_1) using a key (K). M_1 and MAC_1 are then
903   saved or transmitted.

904   •   At a later time, the integrity of the saved or received data is checked. Consider the
905   saved or received data as M_2 and the saved or received MAC as MAC_1.

906   •   Compute a MAC on M_2 using the same key (K), and label that MAC as MAC_2.

907   •   If $MAC_1 = MAC_2$, then it can be assumed that M_2 (the saved or retrieved data) is the
908   same as the data on which MAC_1 was computed (M_1) (i.e., $M_1 = M_2$).

909   Assurance of data integrity is frequently provided using non-cryptographic techniques
910   known as error detection codes. However, these codes can be altered by an adversary to
911   the adversary's benefit. The use of an **approved** cryptographic mechanism, such as a
912   MAC, addresses this problem. That is, the assurance of integrity provided by a MAC is
913   based on the assumption that it is not likely that anyone could correctly generate a MAC
914   without knowing the cryptographic key. An adversary without knowledge of the key will
915   not be able to modify data and then generate a verifiable MAC on the modified data. It is
916   therefore crucial that MAC keys be kept secret.

917 Two types of algorithms for computing a MAC have been **approved** for Federal
918 Government use: MAC algorithms that are based on symmetric-key block cipher
919 algorithms, and MAC algorithms that are based on hash or hash-related functions.

4.2.2.1   MACs Based on Block Cipher Algorithms

921 The SP 800-38 series of publications includes modes for the generation of MACs:

922 • SP 800-38B defines the CMAC mode for computing a MAC using the AES and
923   TDEA block-cipher algorithms; see Section 3.2.1.2 about the deprecated use of
924   TDEA.

925 • SP 800-38D defines the GMAC mode for the computation of a MAC using AES.

926 • Modes providing both confidentiality (i.e., encryption) and authentication (i.e.,
927   computing a MAC) in a single operation are also defined (see Section 4.3).

4.2.2.2   MACs Based on Hash Functions

929 FIPS 198 defines a MAC (HMAC) that uses a cryptographic hash function in combination
930 with a secret key. HMAC must be used with an **approved** cryptographic hash function (see
931 Section 4.2.1). The security associated with the use of HMAC is discussed in SP 800-107.[57]

932 SP 800-185 defines another MAC algorithm (KMAC) that is based on the extendable
933 output function specified in FIPS 202. Two variations of KMAC have been specified:
934 KMAC 128 and KMAC256. Their security is discussed in SP 800-185.

4.2.3   Digital Signature Algorithms

936 A digital signature algorithm is used with a pair of keys – a private key and a public key –
937 to generate and verify digital signatures. The private key is used to generate signatures and
938 must be known only by the signer (the key-pair owner); the public key is used to verify the
939 signatures. Because of the design of the algorithm, and the methods for generating key
940 pairs, the public key cannot efficiently be used to determine the private key. Since two keys
941 are required for the generation and verification process, digital signature algorithms are
942 classified as asymmetric-key algorithms.

943 A digital signature is represented in a computer as a string of bits and is an electronic
944 analogue of a hand-written signature that can be verified by anyone with access to the
945 public key. The signature can be used to provide assurance of data integrity, identity
946 authentication, source authentication, and to support non-repudiation.

947 Each signer possesses a private and public key pair. Signature generation (with a verifiable
948 digital signature) can be performed only by the party that has access to the private key.
949 Anyone that knows the public key can verify the signature by employing the associated
950 public key. The security of a digital-signature system is dependent on maintaining the
951 secrecy of the signer's private key. Therefore, signers must guard against the unauthorized
952 disclosure of their private keys.

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[57] SP 800-107, *Recommendation for Applications Using Approved Hash Algorithms*.

953   Digital signatures offer protection that is not available by using alternative signature
954   techniques. One such alternative is a digitized signature. A digitized signature is generated
955   by converting a visual form of a handwritten signature to an electronic image (e.g., by
956   scanning it into a computer). Although a digitized signature resembles its handwritten
957   counterpart when printed, it does not provide the same protection as a digital signature.
958   Digitized signatures can be forged and can be duplicated and appended to other electronic
959   data; digitized signatures also cannot be used to determine if information has been altered
960   after it is signed. Digital signatures, however, are computed on each message using a
961   private key known only by the signer. Each different message signed by the signer will
962   have a different digital signature. Even small changes to the message will result in a
963   different signature. If an adversary does not know the private key, the adversary cannot
964   generate a valid signature (i.e., a signature that can be verified using the public key that
965   corresponds to the private key used to generate the signature).

966
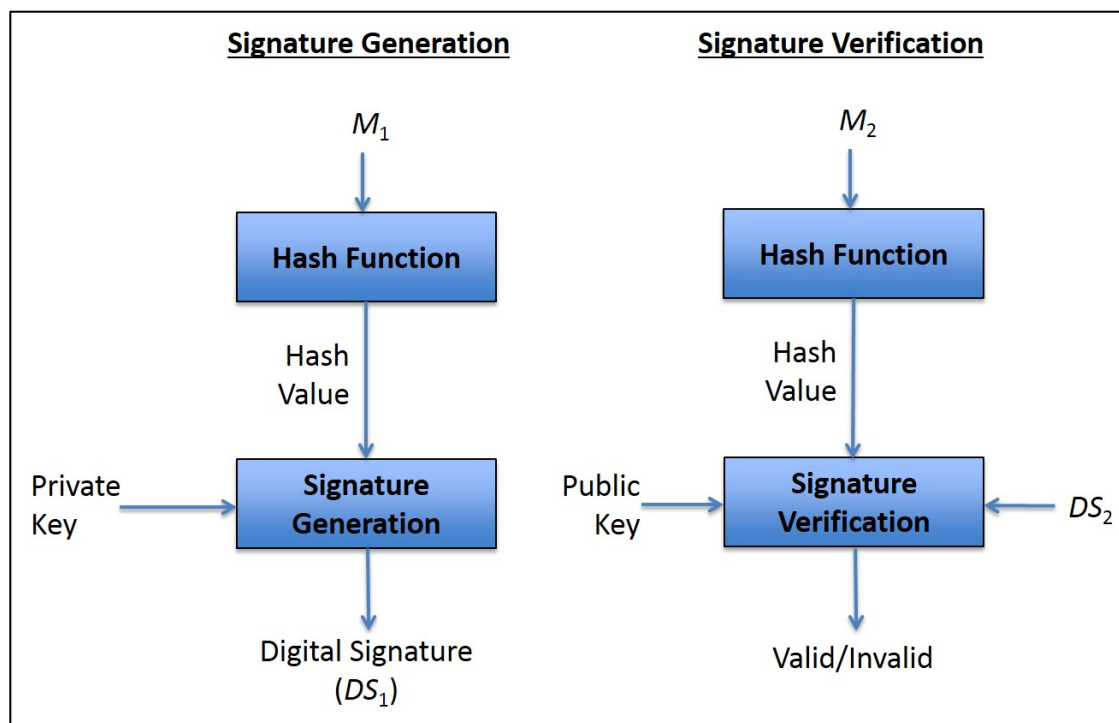
967   **Figure 4: Digital Signature Generation and Verification**

968   Figure 4 depicts the generation and verification of digital signatures. A digital signature
969   algorithm includes a signature generation process and a signature verification process:

970   a. Signature generation:
971   1. A hash function (see Section 3.1) is used in the signature generation process to
972   obtain a hash value, which is a condensed version of the data to be signed (i.e.,
973   shown as M_1 for signature generation in Figure 4).

974   2. The hash value is then input to the signature generation process, along with a
975   private key, to generate the digital signature (shown as DS_1 in Figure 4).

3. The digital signature (DS_1) is provided to the verifier, along with the data that has been signed (M_1), i.e., DS_1 and M_1 are either transmitted to an intended receiver(s) or stored for later retrieval.

b. Signature verification: The receiver of the transmitted data and signature (or the entity retrieving the data and signature from storage) verifies the signature as follows:

1. The received/retrieved data (M_2)[58] is hashed using the same hash function that was used during signature generation to produce another hash value. (Note that if the data was modified during transmission/storage, the newly computed hash value will not be the same as the hash value computed during signature generation (in step a.1).

2. The newly computed hash value and the received/retrieved signature (DS_2)[59] are input to the signature verification process, along with the the signer's public key. The output of this process is an indication of whether or not the signature is valid or invalid for the received/retrieved data (M_2).

FIPS 186 specifies methods for generating and verifying digital signatures using asymmetric (public-key) cryptography. The FIPS includes four digital signature algorithms:

- The Digital Signature Algorithm (DSA) (see Section 3.3.1.1),

- The Elliptic Curve Digital Signature Algorithm (ECDSA) (see Section 3.3.1.2),

- The Edwards-Curve Digital Signature Algorithm (EdDSA) (see Section 3.3.1.3), and

- RSA (see Section 3.3.1.4).

The digital signature algorithms are used in conjunction with the hash functions specified in FIPS 180, FIPS 202 and SP 800-185. Each of these algorithms requires obtaining assurances about the domain parameters and/or keys used, as discussed in Section 3.3; SP 800-89[60] provides methods for obtaining these required assurances when using digital signatures.

In many cases, determining when a digital signature was generated is important. For example, it may be important to determine whether a document was signed before a certain date, e.g., which of two wills was signed closest to and prior to the date that a person died. SP 800-102[61] provides guidance on establishing when a digital signature was generated.

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[58] Since a transmission/storage error may have occurred, or a malicious adversary may have modified the data while in transit/storage, the received/retrieved data may be different than the data that was hashed during signature generation (see step a.1). Therefore, the received/retrieved data is called M_2, rather than M_1.

[59] The signature could also have been modified during transmission/storage. Therefore, DS_2 is used, rather than DS_1 (the generated signature from step).

[60] SP 800-89, *Recommendation for Obtaining Assurances for Digital Signature Applications*.

[61] SP 800-102, *Recommendation for Digital Signature Timeliness*.

4.3   Combining Confidentiality and Authentication in a Block-Cipher Mode of Operation

Confidentiality and authentication can be provided using either two separate block-cipher algorithms (e.g., AES in the CBC mode for encryption and HMAC for authentication) or in a single block-cipher mode of operation. Note that in this discussion, authentication is used to obtain both an assurance of data integrity and of the source of the data that has been cryptographically protected.

If encryption and authentication are performed as two separate operations (see Sections 4.1 and 4.2, respectively), two distinct keys are required. If care is not taken in performing these operations (e.g., performing the operations in the right order), vulnerabilities can be introduced that may allow attacks.

An alternative is to use modes that both encrypt and authenticate in a single operation using a single key; such a mode is called an "authenticated-encryption" mode. Using such modes requires fewer keys and is generally faster than using two separate operations. Two authenticated-encryption modes have been defined for AES (no such mode has been defined for TDEA):

- SP 800-38C specifies the CCM mode, and

- SP 800-38D defines the Galois/Counter mode (GCM).

4.4   Random Bit Generation

Cryptography and security applications make extensive use of random numbers and random bits. For cryptography, random values are needed to generate cryptographic keys. The term "entropy" is used to describe the amount of randomness in a value, and the amount of entropy determines how hard it is to guess that value.

There are two classes of random bit generators (RBGs): Non-Deterministic Random Bit Generators (NRBGs), sometimes called true random number (or bit) generators, and Deterministic Random Bit Generators (DRBGs), sometimes called pseudorandom bit (or number) generators. Each RBG is dependent on the use of an entropy source to provide unpredictable bits that are outside of human control; these bits are acquired from some physical source, such as thermal noise, ring oscillators or hard-drive seek times. An NRBG is dependent on the availability of new, unused entropy bits produced by the entropy source for every NRBG output. A DRBG is initially "seeded" with entropy produced by an entropy source or using an **approved** method that depends on an entropy source (e.g., an NRBG); depending on the application, the DRBG may or may not receive additional entropy during operation (e.g., by being reseeded).

Several publications have been developed or are currently under development for random-bit generation:

- SP 800-90A specifies **approved** DRBG algorithms, based on the use of hash functions and block-cipher algorithms; DRBGs must be initialized from a randomness source (e.g., an entropy source or an NRBG) that provides sufficient entropy for the security strength(s) to be supported by the DRBG.

1048   • SP 800-90B [62] discusses entropy sources, including the health tests needed to
1049   determine that the entropy source has not failed and includes tests for the validation
1050   of the entropy sources by an accredited lab.

1051   • SP 800-90C [63] provides constructions for the design and implementation of NRBGs
1052   and DRBGs from the algorithms in SP 800-90A and the entropy sources designed
1053   in accordance with SP 800-90B. Note that the NRBGs are constructed to include a
1054   DRBG algorithm from SP 800-90A to provide a fallback capability if an entropy
1055   source failure is not immediately detected.

1056   • SP 800-22 [64] discusses some aspects of selecting and testing random and
1057   pseudorandom number generators. This document includes some criteria for
1058   characterizing and selecting appropriate generators, discusses statistical testing and
1059   its relation to cryptanalysis and provides some recommended statistical tests. These
1060   tests may be useful as a first step in determining whether or not a generator is
1061   suitable for a particular cryptographic application. However, for federal
1062   applications, the RBGs must be validated for compliance to FIPS 140 and the
1063   appropriate parts of SP 800-90.

4.5   Symmetric vs. Asymmetric Cryptography

1065   As discussed in Sections 3.2 and 3.3, when large numbers of cryptographic relationships
1066   are required, the number of initial symmetric keys that will be required may be significantly
1067   larger than the number of public/private key pairs required.

1068   However, a primary advantage of symmetric-key cryptography is speed. Symmetric-key
1069   algorithms are generally significantly faster than asymmetric-key algorithms, and the keys
1070   are shorter in length for the same security strength; the key length may be an important
1071   consideration if memory for storing the keys, or the bandwidth for transporting the keys is
1072   limited. In addition, advances in cryptanalysis and computational efficiency have tended
1073   to reduce the level of protection provided by public-key cryptography more rapidly than
1074   that provided by symmetric-key cryptography. Also, in a potential post-quantum world,
1075   the currently approved asymmetric-key algorithms will not provide adequate protection.

1076   Since asymmetric-key (i.e., public-key) cryptography requires fewer keys overall, and
1077   symmetric-key cryptography is significantly faster, a hybrid approach is often used,
1078   whereby asymmetric-key algorithms are used for the generation and verification of digital
1079   signatures and for initial key establishment, while symmetric-key algorithms are used for
1080   all other purposes (e.g., encryption), especially those involving the protection of large
1081   amounts of data, and for key distribution when entities share an already established
1082   symmetric key (established using manual distribution methods or asymmetric key-
1083   establishment methods). For example, an asymmetric-key system can be used to establish
1084   a symmetric key via a key-agreement or key-transport process (see Sections 5.3.3 and

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[62] SP 800-90B, *Recommendation for the Entropy Sources Used for Random Bit Generation*.

[63] SP 800-90C, *Recommendation for Random Bit Generator (RBG) Constructions*.

[64] SP 800-22, *A Statistical Test Suite for Random and Pseudorandom Number Generators for Cryptographic Applications*.

1085   5.3.4, respectively), after which the symmetric key is used to encrypt files or messages or
1086   to distribute other keys.

1087   In some situations, asymmetric-key cryptography is not necessary, and symmetric-key
1088   cryptography alone is sufficient. This includes environments where secure symmetric-key
1089   establishment can take place using symmetric keys already shared between entities,
1090   environments where a single authority knows and manages all the keys, and in single-user
1091   environments.

1092   In general, asymmetric cryptography is best suited for an open, multi-user environment.
1093   However, with the impending availability of quantum computing, the current asymmetric
1094   algorithms will become vulnerable to attacks (see the note in Section 3.3).

5.0   KEY MANAGEMENT

The proper management of cryptographic keys is essential to the effective use of cryptography for security. Keys are analogous to the combination of a safe. If a safe combination becomes known by an adversary, that safe provides no security against penetration by that adversary. Similarly, poor key management may easily compromise strong algorithms. Ultimately, the security of information protected by cryptography directly depends on the strength of the keys, the effectiveness of mechanisms and protocols associated with keys, and the protection afforded to all key information – the keying material and all information associated with that keying material (i.e., the key's metadata). See SP 800-57, Part 1 for a suggested list of the metadata that may be appropriate.

All key information needs to be protected against modification (i.e., the integrity needs to be preserved), and secret and private keys (i.e., keys used by symmetric and asymmetric algorithms, respectively) and any secret metadata need to be protected against unauthorized disclosure (i.e., their confidentiality needs to be maintained).

Key management provides the foundation for the secure generation, storage, distribution/establishment, use and destruction of keys, and is essential at all phases of a key's life. If a strong algorithm is used to encrypt data using keys that are properly generated, then the protection of that data can subsequently be reduced to just protecting the key information, i.e. the security of information protected by cryptography directly depends on the protection afforded the key information. Therefore, a Cryptographic Key Management System (CKMS) is required for managing the keys and the information associated with it.

5.1   General Key Management Guidance

Several publications have been developed to provide general key-management guidance: SP 800-57 (see Section 5.1.1), FIPS 140 (see Section 5.1.2), and SP 800-131A (see Section 5.1.3).

5.1.1   Recommendation for Key Management

SP 800-57 provides general guidance on the management of cryptographic keys and associated information: their generation, use, and eventual destruction. Related topics, such as algorithm selection and appropriate key size, and cryptographic policy are also included in SP 800-57, which consists of three parts:

- SP 800-57, Part 1, *General Guidance*, contains basic key-management guidance, including:
    - o   The protection required for keying material;
    - o   Key life-cycle responsibilities;
    - o   Key backup, archiving and recovery;
    - o   Changing keys;
    - o   Cryptoperiods (i.e., the appropriate lengths of time that keys are to be used);
    - o   Accountability and auditing;

1134   o   Key inventories;

1135   o   Contingency planning; and

1136   o   Key compromise recovery (e.g., by generating new keys).

1137   Federal agencies have a variety of information that they have determined to require
1138   cryptographic protection; the sensitivity of the information and the periods of time
1139   that the protection is required also vary. To this end, NIST has established four
1140   security strengths for the protection of information: 112, 128, 192 and 256 bits.[65]
1141   These security strengths have been assigned to the **approved** cryptographic
1142   algorithms and key sizes, and dates have been projected during which the use of
1143   these algorithms and key sizes is anticipated to be secure. For further information,
1144   see SP 800-131A (discussed in Section 5.1.3).

1145   Agencies need to determine the length of time that cryptographic protection is
1146   required before selecting an algorithm and key size with the appropriate security
1147   strength.

1148   Note that SP 800-57, Part 1 is updated whenever the guidance provided therein is
1149   no longer valid (e.g., an algorithm no longer provides adequate security).

1150   • SP 800-57, Part 2, *Best Practices for Key Management Organization*:

1151   o   Identifies the concepts, functions and elements common to effective
1152   systems for the management of symmetric and asymmetric keys;

1153   o   Identifies the security-planning requirements and documentation necessary
1154   for effective institutional key management;

1155   o   Describes key-management specification requirements;

1156   o   Describes cryptographic key-management policy documentation that is
1157   needed by organizations that use cryptography; and

1158   o   Describes key-management practice-statement requirements.

1159   • SP 800-57, Part 3, *Application-Specific Key Management Guidance*, addresses the
1160   key-management issues associated with currently available cryptographic
1161   mechanisms, such as the Public Key infrastructure (PKI), Internet Protocol Security
1162   (IPsec), Secure/Multipart Internet Mail Extensions (S/MIME), Kerberos, Over-the-
1163   Air Rekeying (OTAR), Domain Name System Security Extensions (DNSSEC),
1164   Encrypted File Systems and the Secure Shell (SSH) protocol.

1165   Specific guidance is provided regarding:

1166   o   The recommended and/or allowable algorithm suites and key sizes,

1167   o   Recommendations for the use of the mechanism in its current form for the
1168   protection of Federal Government information, and

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[65] A fifth security strength (i.e., 80 bits of security) was acceptable for applying cryptographic protection
(e.g., encryption) prior to 2014. However, this strength is no longer adequate.

1169   o   Security considerations that may affect the effectiveness of key-
1170   management processes and the cryptographic mechanisms using keys that
1171   are generated and managed by those key-management processes.

1172   Note that the Transport Layer Security (TLS) protocol was included in the original
1173   version of this document; however, Part 3 now references a separate document that
1174   discusses TLS (see SP 800-52[66]).

1175   New key-management techniques and mechanisms are constantly being developed,
1176   and existing key-management mechanisms and techniques are constantly being
1177   refined. While the security-guidance information contained in Part 3 will be
1178   updated as mechanisms and techniques evolve, new products and technical
1179   specifications can always be expected that are not reflected in the current version
1180   of the document. Therefore, the context provided may include status information,
1181   such as version numbers or implementation status at the time that the document was
1182   last revised.

5.1.2   Security Requirements for Cryptographic Modules

1184   FIPS 140 provides minimum security requirements for cryptographic modules that embody
1185   or support cryptography in federal information systems. A cryptographic module performs
1186   the actual cryptographic computations for a security system protecting sensitive
1187   information. The security requirements cover areas related to the secure design and
1188   implementation of a cryptographic module, including the module specification;
1189   cryptographic module ports and interfaces; roles, services and authentication; finite-state
1190   models; physical security; the operational environment; cryptographic key management;
1191   electromagnetic interference/electromagnetic compatibility (EMI/EMC); self-tests; design
1192   assurance; and the mitigation of attacks.

1193   FIPS 140 is applicable to all federal agencies that use cryptography to protect sensitive
1194   information in computer and telecommunications systems. Further information about FIPS
1195   140   and   the   validation   of   cryptographic   modules   is   available   at
1196   https://csrc.nist.gov/Projects/Cryptographic-Module-Validation-Program.

5.1.3   Transitions to New Cryptographic Algorithms and Key Lengths

1198   With the development and publication of SP 800-57, Part 1, NIST provided
1199   recommendations for transitioning to new cryptographic algorithms and key lengths
1200   because of algorithm breaks or the availability of more powerful computers that could be
1201   used to efficiently search for cryptographic keys. SP 800-131A was developed to provide
1202   more specific guidance for such transitions. Each algorithm and service is addressed in SP

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[66] SP 800-52, *Guidelines for the Selection, Configuration, and Use of Transport Layer Security (TLS)
Implementations.*

1203   800-131A, indicating whether its use is acceptable,[67] deprecated,[68] allowed only for legacy
1204   applications[69] or disallowed.

1205   Note that SP 800-131A is updated when necessary (e.g., to provide a transition schedule
1206   for an algorithm that no longer provides adequate security).

5.2   Cryptographic Key Management Systems

1208   Several publications have been developed for the development of key-management
1209   systems: SP 800-130[70] (see Section 5.2.1), SP 800-152[71] (see Section 5.2.2) and
1210   documents relating to the Public Key Infrastructure used for asymmetric-key cryptography
1211   (see Section 5.2.3).

1212   A Cryptographic Key Management System (CKMS) includes policies, procedures,
1213   components and devices that are used to protect, manage and distribute key information.
1214   A CKMS includes all devices or subsystems that can access a key or the other information
1215   associated with it. The devices could be computers, cell phones, tablets, or other smart
1216   devices, such as cars, alarm systems, or even refrigerators.

5.2.1   Key Management Framework

1218   SP 800-130 contains topics that should be considered by a CKMS designer when
1219   developing a CKMS design specification. Topics include security policies, cryptographic
1220   keys and metadata, interoperability and transitioning, security controls, testing and system
1221   assurances, disaster recovery, and security assessments.

1222   For each topic, SP 800-130 specifies one or more documentation requirements that need to
1223   be addressed by the designer. SP 800-130 is intended to assist in:

1224   • The definition of the CKMS design by requiring the specification of significant
1225   CKMS capabilities,

1226   • Encouraging CKMS designers to consider the factors needed in a comprehensive
1227   CKMS,

1228   • Logically comparing different CKMSs and their capabilities,

1229   • Performing security assessments by requiring the specification of implemented and
1230   supported CKMS capabilities, and

1231   • Forming the basis for the development of Profiles that specify the specific
1232   requirements for the CKMS to be used by an organization.

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[67] No security risk is known at present.

[68] The use of the algorithm and key length is allowed, but the user must accept some risk.

[69] The algorithm and key length may be used to process already-protected information, but there may be a
    risk in doing so.

[70] SP 800-130, *A Framework for Designing Cryptographic Key Management Systems*.

[71] SP 800-152, *A Profile for U. S. Federal Cryptographic Key Management Systems (CKMS)*.

5.2.2   Key Management System Profile

SP 800-152 contains requirements for the design, implementation, procurement, installation, configuration, management, operation and use of a CKMS by and for U.S. federal organizations and their contractors. The Profile is based on SP 800-130 (see Section 5.2.1). SP 800-152 specifies requirements, makes recommendations for federal organizations having special security needs and desiring to augment the base security and key-management services, and suggests additional features that may be desirable to implement and use.

In addition to providing design requirements to be incorporated into a CKMS design, SP 800-152 provides requirements for a Federal CKMS (FCKMS) to be operated by a service provider that may be a federal agency or a third party operating an FCKMS under contract for one or more federal agencies and their contractors.

This Profile is intended to:

- Assist CKMS designers and implementers in supporting appropriate cryptographic algorithms and keys, selecting the metadata associated with the keys, and selecting protocols for protecting sensitive U.S. federal computing applications and data;

- Establish requirements for testing, procurement, installation, configuration, administration, operation, maintenance and usage of the FCKMS;

- Facilitate an easy comparison of one CKMS with another by analyzing their designs and implementations in order to understand how each meets the Framework (i.e., SP 800-130) and Profile (e.g., SP 800-152) requirements; and

- Assist in understanding what is needed to evaluate, procure, install, configure, administer, operate, and use an FCKMS that manages the key information that is used to protect sensitive and valuable data obtained, processed, stored, and used by U.S. federal organizations and their contractors.

5.2.3   Public Key Infrastructure

A PKI is a security infrastructure that creates and manages public-key certificates to facilitate the use of public-key (i.e., asymmetric-key) cryptography. To achieve this goal, a PKI needs to perform two basic tasks:

1. Generate and provide public key certificates that bind public keys to the identifier associated with the owner of the corresponding private key[72] and to other required information *after* validating the accuracy of the information to be bound, and

2. Maintain and provide certificate-status information for unexpired and revoked certificates.

Two types of certificates are commonly used: certificates used to provide the public keys that are used to verify digital signatures, and certificates used to provide the public keys used for key establishment. Each certificate associated with digital signatures provides the

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[72] The identifier could be the true identity of the owner, or could be an alias or a pseudonym used to represent the owner.

1270 public keys of one of the digital-signature algorithms approved in FIPS 186: DSA, ECDSA,
1271 EdDSA or RSA (see Section 3.3). Certificates that convey the public keys to be used for
1272 key establishment may be of two types: those that provide a key-agreement public key (see
1273 Section 5.3.3), and those that provide a key-transport public key (see Section 5.3.4). Key-
1274 usage bits in a certificate indicate the purpose for which the public key is intended to be
1275 used.

1276 As discussed in Section 3.3, public keys can be made available to anyone. However, a
1277 private key must be kept secret and used only by the entity that owns and is authorized to
1278 use the key. An entity may be a person, organization, device or process, including network
1279 servers. In the case of non-human entities (e.g., devices or processes), one or more humans
1280 are assigned as representatives or sponsors of that entity for managing its key information;
1281 the representative or sponsor **should not** have access to any secret key information once
1282 entered into the system. In this case, the owner of the private key (e.g., a device or process)
1283 is not the same as the owner of the certificate (i.e., the human representative or sponsor).

1284 A relying party is an entity that relies on the certificate and the CA that issued the certificate
1285 to verify the identity of the certificate owner, and the validity of the public key, associated
1286 algorithms and any relevant parameters in the certificate, as well as the private-key owner's
1287 possession of the corresponding private key.

1288 The loss or compromise of the private key has the following implications:

1289 • If a private key that is used to generate digital signatures is lost, the owner can no
1290   longer generate digital signatures; some policies may permit backup copies of the
1291   private key to be maintained for continuity of operations, but this is not encouraged,
1292   so an alternative is to simply generate new key pairs and certificates.

1293 • If the private key used to generate digital signatures is compromised, relying parties
1294   can no longer trust the digital signatures generated using that private key (e.g.,
1295   someone may be using the signature to provide false information).

1296 • If a private key used for key establishment is lost (e.g., a key used for key transport
1297   or key agreement), then further key establishment processes cannot be
1298   accomplished until the key is recovered or replaced; if the key is needed to recover
1299   data protected by the key, then that data is lost unless the key can be recovered. For
1300   example, if the key is used to transport a decryption key for encrypted data, and the
1301   key is lost, then the encrypted data cannot be decrypted. To ensure that access to
1302   critical data is not lost, PKIs often backup the private key-establishment key for
1303   possible recovery.

1304 • If a private key used for key establishment is compromised, then any transactions
1305   involving that key cannot be trusted (e.g., someone other than the true owner of the
1306   private key may be attempting to enter into a supposedly "secure" transaction for
1307   some illicit purpose).

5.2.3.1   PKI Components, Relying Parties and Their Responsibilities

1309 For scalability, PKIs are usually implemented with a set of complementary components,
1310 each focused on specific aspects of the PKI process. The main PKI tasks are assigned to

1311　the following logical components; other components are also used to support the PKI, but
1312　are not discussed here (see SP 800-32[73] for further discussion):

1313　　• *Certification authorities* (CAs) generate certificates and certificate-status
1314　　　information, and

1315　　• *Registration authorities* (RAs) verify the identity of users applying for a
1316　　　certificate[74] and authenticate other information to be included in the certificate.

1317　In general, a PKI operates as follows:

1318　　1.　An application for a certificate is presented to an RA.

1319　　2.　The RA a) verifies the identity of the applicant and the authorization of the
1320　　　　applicant to obtain a certificate and b) verifies the information to be inserted in the
1321　　　　certificate.

1322　　3.　If the checks made by the RA in step 2 indicate that the information to be inserted
1323　　　　in the certificate is valid, and the identity and authorization of the applicant has
1324　　　　been verified, then the RA sends the public key and other relevant information to
1325　　　　the CA to request that a certificate be generated.

1326　　4.　Upon receiving the certificate request from the RA, the CA creates a digital
1327　　　　certificate, makes the certificate available to the RA and/or the applicant and
1328　　　　deposits the certificate in a repository. The RA or CA should also create an
1329　　　　inventory of all certificates.

1330　　5.　When a relying party interacts with another entity that has a public-key certificate,
1331　　　　the relying party needs to obtain the other entity's certificate, either directly from
1332　　　　the other entity or from the repository where it is stored. After acquiring the
1333　　　　certificate, the relying party verifies the signature on the certificate. Assuming that
1334　　　　the certificate is "good," then the relying party can proceed safely with its
1335　　　　interaction with the public key owner.

1336　Most of the interaction involved with using a certificate is transparent to the user (i.e., the
1337　relying party). However, a user or a system administrator may be responsible for obtaining
1338　and installing a certificate. Thereafter, an application (e.g., a browser) uses the certificate
1339　to interact with other entities, and the user may not be aware of these actions. An exception
1340　might be when a certificate has expired or been revoked, in which case a message may be
1341　displayed to indicate this status.

1342　Certificates expire at a predetermined time. In many cases, services are denied when
1343　certificates expire. A certificate inventory can be used to identify certificates that are
1344　nearing expiration, allowing time to replace these certificates prior to their expiration, thus
1345　avoiding service outages. A certificate inventory can also be used to detect the use of
1346　algorithms and key lengths that are no longer secure, respond to cryptographic incidents
1347　(e.g., a CA compromise), and modify who should be contacted for certificate maintenance
1348　(e.g., the certificate owner).

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[73] SP 800-32, *Introduction to Public Key Technology and the Federal PKI Infrastructure*.

[74] The certificate could be for the user or for a device for which the user is authorized to obtain a certificate.

1349 Certificates may be revoked prior to the expiration date (e.g., using a Certificate
1350 Revocation List that identifies revoked certificates). Certificates can be revoked for a
1351 variety of reasons, including the compromise of the private key corresponding to the public
1352 key in the certificate, or the owner of the certificate leaving the organization. When a
1353 certificate has been revoked, a system will quite often display the certificate-revocation
1354 message and perhaps include the reason for the revocation. Depending on the application
1355 implementation and the revocation reason, the application could disallow further actions,
1356 or could allow the user (i.e., the relying party) to indicate whether to ignore the warning
1357 and continue operations, or to simply discontinue operations. This warning must not be
1358 taken lightly. Ignoring the warning means that the user is accepting the risks associated
1359 with doing so. For example, if a warning indicates a compromised digital signature
1360 certificate, there is a possibility that someone other than the claimed owner of the certificate
1361 actually used the private key corresponding to the public key to sign data. Depending on
1362 the data, it may not be prudent to ignore the warning. A user should consult with his
1363 organization to determine how to respond to this warning.

5.2.3.2 Basic Certificate Verification Process

1365 A PKI consists of at least one CA with its subscribers, as shown in Figure 5. Each of the
1366 subscribers (e.g., User 1, User 2 and User 3) obtains a certificate containing their public
1367 key and other information, which is signed by their CA. All CA subscribers are provided
1368 with the public key of the CA.

1369 As a basic example of how this works, suppose that User 3 signs a document and sends the
1370 signed document to User 1, who needs to verify the contents and source of the signed
1371 document. This is accomplished as follows:

1372   1. User 1 obtains the certificate containing the
1373   public key that corresponds to the private key
1374   used to sign the document, i.e., User 1 obtains
1375   User 3's certificate. Either User 3 supplies
1376   that certificate, or the certificate is obtained
1377   from some other source, e.g., the CA.

1378   2. User 1 verifies User 3's certificate using the
1379   CA's public key.

1380   3. User 1 then employs the public key in User
1381   3's certificate to verify the signature on the
1382   signed document received from User 3. If the
1383   signature is successfully verified, then User 1
1384   knows that User 3 generated the signature,
1385   and no unauthorized modifications were
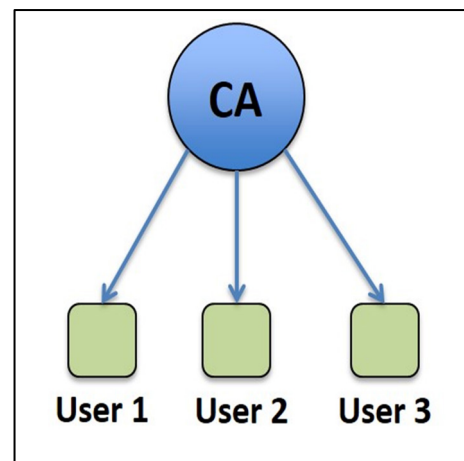1386   made to the document after the signature was
1387   generated.

Figure 5: Basic Certificate Verification Example

1388 Note that other more-complicated scenarios exist when users subscribing to different CAs
1389 need to interact using CAs that have cross certified by signing a certificate for each other.

1390 **5.2.3.3   CA Certificate Policies and Certificate Practice Statements**

1391 Each CA has a Certificate Policy and a Certificate Practices Statement. As defined by
1392 ITU[75] Recommendation X.509, a Certificate Policy (CP) is "a named set of rules that
1393 indicates the applicability of a certificate to a particular community and/or class of
1394 applications with common security requirements." The CP defines the expectations and
1395 requirements of the relying party community that will trust the certificates issued by the
1396 CAs using that policy. A CP addresses such issues as key generation and storage; certificate
1397 generation; key escrow[76] and key recovery; certificate status services, including Certificate
1398 Revocation List (CRL) generation and distribution; and system management functions,
1399 such as security audits, configuration management, and archiving.

1400 A Certification Practice Statement (CPS) describes how a specific CA issues and manages
1401 public-key certificates. The CPS is derived from the applicable CP for the community or
1402 application in which the CA participates.

1403 A Federal Public Key Infrastructure (FPKI) has been established for use by the Federal
1404 Government (see Section 5.2.3.4 for further information).

1405 DRAFT NISTIR 7924[77] identifies a baseline set of security controls and practices to
1406 support the secure issuance of certificates. NISTIR 7924 is designed to be used as a
1407 template and guide for writing a CP for a specific community, or a CPS for a specific CA.

1408 **5.2.3.4   Federal Public Key Infrastructure**

1409 A Federal Public Key Infrastructure (FPKI) provides the Federal Government with a
1410 common infrastructure to administer digital certificates and public-private key pairs. The
1411 network portion of the FPKI (commonly referred to as the "Bridge") consists of "Principal
1412 CAs" designated by various agencies. Each CA within the bridge is cross-certified with
1413 every other CA within the bridge, thus establishing a conduit for trust relationships among
1414 all CAs within the FPKI. Each Principal CA may also be associated with other CAs that
1415 are not part of the bridge. For more information about the FPKI, including its certificate
1416 policy and certificate practices statement, see http://www.idmanagement.gov/federal-
1417 public-key-infrastructure.

1418 ## 5.3   Key Establishment

1419 Key establishment is the means by which keys are generated and provided to the entities
1420 that are authorized to use them. Scenarios for which key establishment could be performed
1421 include the following:

1422 • A single entity could generate a key (see Section 5.3.1) and use it without providing
1423   it to other entities (e.g., for protecting locally stored data),

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[75] International Telecommunication Union.

[76] Saving a key or information that allows the key to be reconstructed so that the key can be recovered if ever
     needed (e.g., because of being lost or corrupted).

[77] NISTIR 7924, *Reference Certificate Policy (Second Draft)*.

1424 • A key could be derived from a key that is already shared between two or more
1425 　 entities (see Section 5.3.2),

1426 • Two entities could generate a key using contributions (i.e., data) from each entity
1427 　 using an automated protocol that incorporates a key-agreement scheme (see Section
1428 　 5.3.3), or

1429 • A single entity could generate a key and provide it to one or more other entities,
1430 　 either by a manual means (e.g., a courier or a face-to-face meeting, with the key in
1431 　 either printed or electronic form, such as on a flash drive) or using automated
1432 　 protocols that incorporate a key-transport scheme (see Sections 5.3.4 and 5.3.5).

5.3.1 Key Generation

1434 Cryptographic keys are required by most cryptographic algorithms, the exception being
1435 hash functions when not used as a component of another cryptographic process (e.g.,
1436 HMAC). SP 800-133[78] discusses the generation of the keys to be used with the **approved**
1437 cryptographic algorithms.

1438 All keys must be based directly or indirectly on the output of an **approved** Random Bit
1439 Generator (RBG) and must be generated within FIPS 140-compliant cryptographic
1440 modules (see FIPS 140). Any random value required by the module must be generated
1441 within a cryptographic module.

1442 SP 800-133 provides guidance on generating a key directly from an RBG, and references
1443 other publications for additional information required for the generation of keys for specific
1444 algorithms:

1445 • FIPS 186 provides rules for the generation of the key pairs to be used for the
1446 　 generation of digital signatures,

1447 • SP 800-108 provides methods for the generation of keys from a pre-shared key
1448 　 (also see Section 5.3.2 below),

1449 • SP 800-56A specifies the rules for the generation of key pairs for Diffie-Hellman
1450 　 and MQV key-agreement schemes (also see Section 5.3.3 below),

1451 • SP 800-56B specifies the rules for the generation of key pairs for RSA key-
1452 　 agreement and key-transport schemes (also see Sections 5.3.3 and 5.3.4 below and

1453 • SP 800-132[79] specifies the rules for the generation of keys from passwords (also
1454 　 see Section 5.3.7 below).

5.3.2 Key Derivation

1456 Key derivation is concerned with the generation of a key from secret information, although
1457 non-secret information may also be used in the generation process in addition to the secret
1458 information. Typically, the secret information is shared among entities that need to derive
1459 the same key for subsequent interactions. The secret information could be a key that is

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[78] SP 800-133, *Recommendation for Cryptographic Key Generation*.
[79] SP 800-132, *Recommendation for Password-Based Key Derivation, Part 1: Storage Applications.*

1460 already shared between the entities (i.e., a pre-shared key), or could be a shared secret that
1461 is derived during a key-agreement scheme (see Section 5.3.3).

1462 SP 800-108 specifies several key-derivation functions that use pre-shared keys. A pre-
1463 shared key could have been

1464 • Generated by one entity and provided to one or more other entities by some manual
1465 means (e.g., a courier or face-to-face meeting),

1466 • Agreed upon by the entities using an automated key-agreement scheme (see Section
1467 5.3.3), or

1468 • Generated by one entity and provided to another entity using an automated key-
1469 transport scheme (see Sections 5.3.4 and 5.3.5).

1470 SP 800-56C and SP 800-135[80] provide methods for deriving keys from the shared secrets
1471 generated during key agreement (see Section 5.3.3).

1472　5.3.3　Key Agreement

1473 Key agreement is a key-establishment procedure in which the resultant keying material is
1474 a function of information contributed by all participants in the key-agreement process so
1475 that no participant can predetermine the value of the resulting keying material
1476 independently of the contributions of the other participants. Key agreement is usually
1477 performed using automated protocols.

1478 SP 800-56A and SP 800-56B provide several automated pair-wise key-agreement schemes,
1479 i.e., key-agreement schemes involving two parties. For each scheme, a shared secret is
1480 generated, and keying material is derived from the shared secret using a key-derivation
1481 method specified or approved in SP 800-56C.

1482 SP 800-56A and SP 800-56B include variations of key-agreement schemes, differing in
1483 the number of keys used and whether the keys are long term (i.e., static) or an ephemeral
1484 value (e.g., a nonce or a short-term key pair). The key-agreement schemes have two
1485 participating entities: an initiator and a responder.

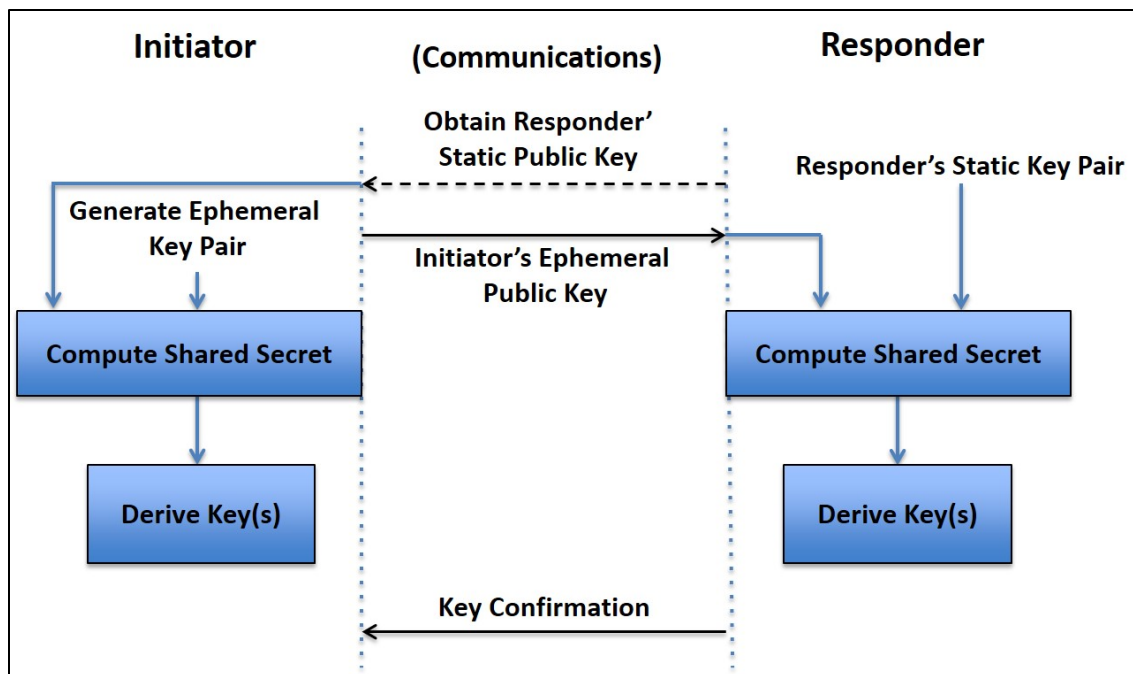[80] SP 800-135, *Recommendation for Existing Application-Specific Key Derivation Functions*.

Figure 6: Key Agreement Example

Figure 6 provides an example of a key-agreement scheme where the responder uses a static key pair during the scheme, and the initiator uses an ephemeral key pair. Note that other key-agreement schemes may use other arrangements of key pairs (e.g., each party could use a static key pair, or each party could use an ephemeral key pair). In the example provided in the figure above, the responder's private key is retained by the responder (who is the owner of the key pair), but the responder's public key may be provided to anyone. In this example, the public key is provided to the initiator:

1. The initiator obtains the responder's public key (e.g., from a CA or directly from the responder); for this scheme, this public key is the responder's contribution to the key-agreement process.

2. The initiator then generates a short-term key pair (i.e., an ephemeral key pair), and sends the ephemeral public key to the responder, retaining the ephemeral private key. The ephemeral public key is the initiator's contribution to the key-agreement process for this scheme.

3. Both parties use their own key pair and the other party's public key to generate a shared secret.

4. Both parties then use their copy of the shared secret to derive one or more keys that are (hopefully) identical.

Key confirmation is an optional, but highly recommended, step that provides assurance that both parties now have the same (identical) key(s), and is shown in Figure 6 for the case that the initiator receives key confirmation from the responder. See SP 800-56A and SP 800-56B for further information.

53

1510 SP 800-56A specifies Diffie-Hellman (DH) and MQV key-agreement schemes using finite
1511 field or elliptic curve mathematics and asymmetric key pairs to generate the shared secret
1512 (see Section 3.3.2.1 above), and SP 800-56B specifies two RSA key-agreement schemes
1513 (see Section 3.3.2.2 above). SP 800-56A and SP 800-56B also provide an analysis of the
1514 security properties provided by each key-agreement scheme.

5.3.4 Key Transport/Key Distribution

1516 Key transport is a method whereby one party (the sender) generates a key and distributes
1517 it to one or more other parties (the receiver(s)). Key transport could be accomplished using
1518 manual methods (e.g., using a courier) or performed using automated protocols. SP 800-
1519 56B provides automated pair-wise key-transport schemes using RSA, and an analysis of
1520 the security properties provided by each key-transport scheme (see Section 5.3.4.1). SP
1521 800-71[81] provides schemes for distributing keying material protected by symmetric-key
1522 block cipher algorithms (e.g., AES) (see Section 5.3.4.2).

5.3.4.1 SP 800-56B Key Transport

1524 SP 800-56B specifies a method for transporting keys whereby the sender uses the receiver's
1525 public key to securely transport keying material to the receiver.

1526 Figure 7 provides a simplified example of the key-transport method in SP 800-56B. The
1527 receiver must have a key pair that is used during a key-transport transaction. Key transport
1528 is accomplished as follows.

1529 The sender:

1530 1. Obtains the public key of the intended receiver,

1531 2. Generates a symmetric key to be transported,

1532 3. Encrypts the symmetric key using the receiver's public key, and

1533 4. Sends the resulting ciphertext key to the receiver.

1534 The receiver:

1535 5. Uses his private key to decrypt the ciphertext key, thus obtaining the original
1536 plaintext key.

1537 6. Optionally performs key confirmation; although this step is optional, it is
1538 highly recommended to provide assurance that both parties now have the same
1539 symmetric key.

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[81] SP 800-71, *Recommendation for Key Establishment Using Symmetric Block Ciphers*.
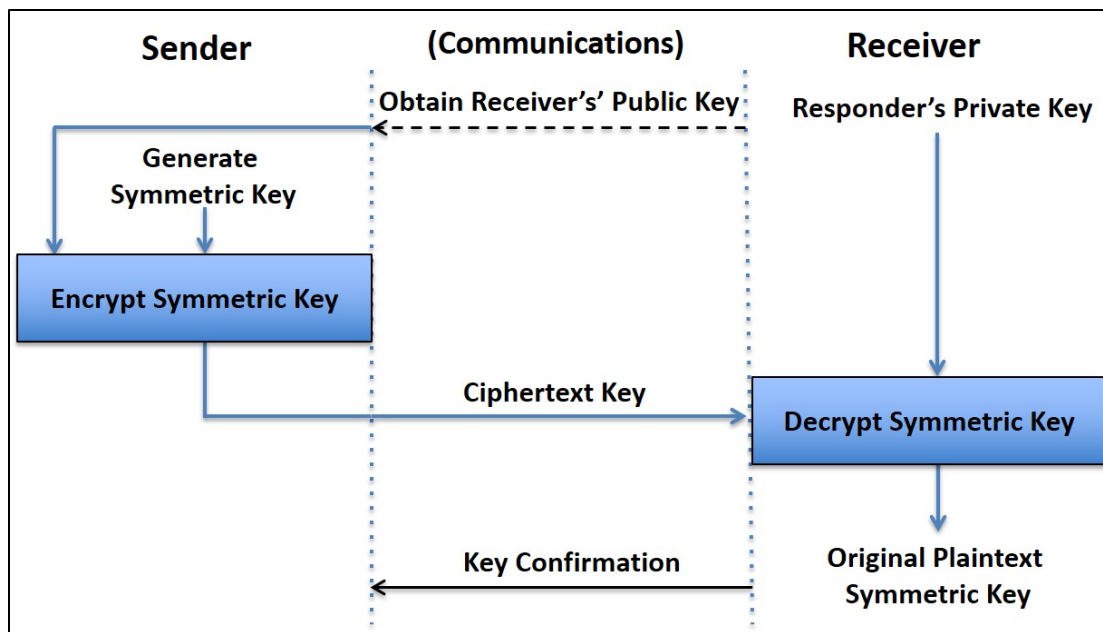
Figure 7: SP 800-56B Key Transport Example

5.3.4.2   SP 800-71 Key Distribution

SP 800-71 addresses the protection of keying material during key distribution using symmetric-key cryptography. Using **approved** key wrapping methods (see Section 5.3.5), techniques are discussed for encrypting keys, binding metadata to the keys and protecting the integrity of the distributed key information.

Several key-distribution architectures are described. These include:

- Key distribution among communicating groups that share a key-wrapping key (e.g., pairs of entities),

- The distribution of keys by key generation and distribution centers to their subscribers,

- The use of key-translation centers for the protected distribution of keys generated by one subscriber for distribution to one or more other subscribers, and

- Multiple-center-based environments for key distribution between or among organizational domains.

SP 800-71 does not specify protocols for key distribution but suggests key-distribution communication options and transaction content that **should** be accommodated by key-distribution protocols.

5.3.5   Key Wrapping

Key wrapping is a method used to provide confidentiality and integrity protection to keys (and possibly other information) using a symmetric-key block cipher algorithm and symmetric key-wrapping keys that are known by both the sender and receiver. The wrapped keying material can then be stored or transmitted (i.e., distributed) securely.

1563   Unwrapping the keying material requires the use of the same algorithm and key-wrapping
1564   key that was used during the original wrapping process.

1565   Key wrapping differs from simple encryption in that the wrapping process includes both
1566   encryption and integrity protection. During the unwrapping process, a method for integrity
1567   verification is used to detect accidental or intentional modifications to the wrapped keying
1568   material.

1569   SP 800-38F[82] specifies three methods for key wrapping and approves other SP 800-38
1570   modes (or combination of modes) . Depending on the method or mode, either AES or
1571   TDEA can be used.

5.3.6   Derivation of a Key from a Password

1573   Keys can be derived from passwords. Due to the ease of guessing most passwords, keys
1574   derived in this manner are not suitable to be used for most applications. However, SP 800-
1575   132 specifies a family of functions that can be used to derive keying material from a
1576   password[83] for electronic storage applications (e.g., when encrypting an entire disk drive).

5.4   Key Management Issues

1578   A number of issues need to be addressed for selecting and using a CKMS.

5.4.1   Manual vs. Automated Key Establishment

1580   As discussed in Section 5.3, keys can be established between entities either manually or
1581   using automated methods. In many cases, a hybrid approach is used in which an entity
1582   generates and manually distributes one or more keys to other entities, and thereafter these
1583   keys are used to establish other keys (see SP 800-56A, SP 800-56B and SP 800-71).

1584   The number of keys to be manually distributed depends on the type of cryptography to be
1585   used (i.e., symmetric or asymmetric methods) and must be considered when selecting the
1586   capabilities required of a CKMS.

5.4.2   Selecting and Operating a CKMS

1588   A CKMS could be designed, implemented and operated by the organization that will use
1589   it. The organization could operate a CKMS procured from a vendor, or an organization
1590   could procure the services of a third party that procures a CKMS from a vendor. Whichever
1591   choice is made, the organization needs to make sure that the CKMS that is used provides
1592   the protections that are required for the organization's information. SP 800-130 and SP
1593   800-152 discuss the considerations that need to be addressed by a federal organization,
1594   including the scalability of the CKMS, and the metadata to be associated with the keys.

5.4.3   Storing and Protecting Keys

1596   Keys can be stored in a number of places and protected in a variety of ways. They could
1597   be stored in a safe. They could be present only in a validated cryptographic module where

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[82] SP 800-38F, *Recommendation for Block Cipher Modes of Operation: Methods for Key Wrapping*.

[83] Note that this publication considers a passphrase or a PIN to be a password.

1598   the module itself might adequately protect the keys, depending on its design. Keys could
1599   also be stored on electronic media, such as a flash drive; in this case, a key may need to be
1600   wrapped (i.e., encrypted and its integrity protected) or split into key components so that no
1601   single person can determine the key. These issues need to be addressed for operational
1602   keys.

1603   Certain keys may need to be backed up so that if an operational key is inadvertently lost or
1604   modified, it can be recovered and operations resumed. Some keys may also need to be
1605   archived for long-term storage (e.g., because of legal requirements or to decrypt archived
1606   data). A key-recovery capability is needed whenever keys are backed up or archived. This
1607   capability needs to be designed so that the keys can be recovered in an acceptable amount
1608   of time and only by those entities authorized to do so; see SP 800-57, Part 1 for more
1609   information about key backup, key archiving and and the recovery of backed up and
1610   archived keys.

5.4.4   Cryptoperiods

1612   A cryptoperiod is the time span during which a specific key is authorized for use. A
1613   cryptoperiod for a key is assigned for a number of reasons, including limiting the amount
1614   of exposure of encrypted data if a key is compromised. Cryptoperiods are usually assigned
1615   for a carefully considered period of time or by the maximum amount of data to be protected
1616   by the key. Tradeoffs associated with the determination of a cryptoperiod involve the risks
1617   and consequences of exposure. Section 5.3 of SP 800-57, Part 1 provides a more detailed
1618   discussion of the need for establishing cryptoperiods, the factors to be considered when
1619   deciding on a suitable cryptoperiod and some suggestions for the length of cryptoperiods.

5.4.5   Use Validated Algorithms and Cryptographic Modules

1621   Cryptographic algorithms must be validated and implemented in FIPS 140-validated
1622   cryptographic modules. Every IT product available makes a claim as to functionality and/or
1623   offered security. When protecting sensitive data, a minimum level of assurance is needed
1624   that a product's stated security claim is valid. There are also legislative restrictions
1625   regarding certain types of technology, such as cryptography, that require federal agencies
1626   to use only tested and validated products.

1627   Federal agencies, private industry, and the public rely on cryptography for the protection
1628   of information and communications used in electronic commerce, the critical
1629   infrastructure, and other application areas. At the core of all products offering
1630   cryptographic services is the cryptographic module. Cryptographic modules, which contain
1631   cryptographic algorithms, are used in products and systems to provide security services
1632   such as confidentiality, integrity, and authentication. Although cryptography is used to
1633   provide security, weaknesses such as poor design or weak algorithms can render the
1634   product insecure and place highly sensitive information at risk. Adequate testing and
1635   validation of the cryptographic module and its underlying cryptographic algorithms against
1636   established standards is essential to provide security assurance.

1637   NIST has established programs to validate the implementation of the **approved**
1638   cryptographic algorithms and the cryptographic modules in which they are used: the
1639   Cryptographic Algorithm Validation Program (CAVP) and the Cryptographic Module

1640 Validation Program (CMVP). Information about the CAVP is available at
1641 https://csrc.nist.gov/Projects/Cryptographic-Algorithm-Validation-Program, while
1642 information about the CMVP is available at https://csrc.nist.gov/Projects/Cryptographic-
1643 Module-Validation-Program.

1644 Also, see Section 5.1.2 in this document for a discussion of the security requirements for
1645 cryptographic modules.

5.4.6 Control of Keying Material

1646

1647 Access to keys needs to be controlled. A key should only be accessible by an authorized
1648 entity, and only for the purpose for which it is authorized. For example, a key designated
1649 for key transport must not be used for the generation or verification of digital signatures.

1650 The proliferation of keys also needs to be controlled. While it is often convenient to make
1651 copies of keys, these extra copies need to be accounted for. If a key is compromised, that
1652 key and all its copies may need to be destroyed to prevent subsequent unauthorized use.
1653 For example, if a private key used for the generation of a digital signature is compromised,
1654 and a copy of the key still exists after the original copy was destroyed, then there is a
1655 possibility that the copy could be used to generate unauthorized digital signatures at a later
1656 time.

1657 Users must be provided with a list of responsibilities and liabilities, and each user should
1658 sign a statement acknowledging these concerns before receiving a key. Users must be made
1659 aware of their unique responsibilities, especially regarding the significance of a key
1660 compromise or loss. Users must be able to store their secret and private keys securely, so
1661 that no intruder can access them, yet the keys must be readily accessible for legitimate use.

5.4.7 Compromises

1662

1663 It is imperative to have a plan for handling the compromise or suspected compromise of
1664 keys, particularly those used and managed at a central site (e.g., the keys used by a CA to
1665 sign certificates). A compromise-recovery plan should be established before the system
1666 becomes operational and address what actions will be taken with compromised system
1667 software and hardware, CA keys, user keys, previously generated signatures, encrypted
1668 data, etc. SP 800-57, Part 1 includes discussions of the effects of a key compromise,
1669 measures for minimizing the likelihood or consequences of a key compromise, and what
1670 should be considered in developing a compromise-recovery plan.

1671 If someone's private or secret key is lost or compromised, other users must be made aware
1672 of this so that they will no longer initiate the protection of data using a compromised key,
1673 or accept data protected with a compromised key without assessing and accepting the risk
1674 of doing so. This notification is often accomplished using CRLs or Compromised Key Lists
1675 (CKLs); see SP 800-57, Part 1 for discussions.

1676 In some cases, a key and all copies of the key should be destroyed immediately upon the
1677 detection of a key compromise. For example, a private key used for the generation of digital
1678 signatures should be immediately destroyed. However, the corresponding public key may
1679 need to remain available for verifying the signatures that were previously generated using

1680   the compromised private key. Note that there is a risk associated with accepting these
1681   signatures.

5.4.8   Accountability and Inventory Management

1682

1683   Accountability involves the identification of those entities that have access to or control of
1684   cryptographic keys or certificates throughout their lifecycles. Accountability can be an
1685   effective tool to help prevent key compromises and to reduce the impact of compromises
1686   when they are detected, helping to determine the individuals that could have been involved
1687   when a compromise occurs, discouraging key compromise because users know their access
1688   to the key is known, and determining where the key was used and what data or other keys
1689   were protected by a compromised key, and therefore, may also be compromised. When
1690   public key certificates are used, accountabiliy is used to determine who is reponsible for
1691   certificate maintenance (e.g., certificate replacement when a certificate expires or a private
1692   key is compromised).

1693   The use of a key or certificate inventory can be used as a tool for assisting with
1694   accountability. Inventory management is concerned with establishing and maintaining an
1695   inventory of keys and/or certificates; assigning and tracking their owners, representatives
1696   or sponsors (e.g., who/what they are, where they are located and how to contact them);
1697   automating the entry of keys and certificates into the inventory; monitoring key and
1698   certificate status (e.g., expiration dates and whether a key has been compromised), and
1699   reporting the status to the appropriate official for remedial action, when required. SP 800-
1700   57, Part 1 provides discussions on both key and certificate inventory management.

5.4.9   Auditing

1701

1702   Auditing is a mechanism used for the prevention, detection and recovery from key
1703   compromises. Several types of auditing need to be performed to assure proper key
1704   management:

1705   • A compliance audit is a comprehensive review of an organization's adherence to
1706   regulatory guidelines. Compliance auditors review security policies (e.g., key
1707   management policies), as well as user access controls and risk-management
1708   procedures to determine that these controls and procedures support the policies.

1709   • An audit of the protective mechanisms employed (e.g., the cryptographic
1710   algorithms and key lengths used) is needed to reassess the level of security currently
1711   provided and expected to be required and provided in the future. This is needed to
1712   determine that the mechanisms correctly and effectively support the appropriate
1713   policies (e.g., the key management policies). New technology developments and
1714   attacks need to be taken into consideration.

1715   • An audit of the actions of the humans that use, operate and maintain the key
1716   management system is needed to verify that the humans continue to follow
1717   established security procedures. Highly unusual events are noted and reviewed as
1718   possible indicators of attempted attacks on the system.

1719

1720

1721
6.0   OTHER ISSUES

1723 The use of cryptography should not be undertaken without a thorough risk analysis, and a
1724 determination of the sensitivity of the information to be protected and the security controls
1725 to be used (see FIPS 199, SP 800-175A and SP 800-53). After performing a risk assessment
1726 and determining the sensitivity level of the information to be protected (Low, Moderate or
1727 High) and the security controls to be used, a number of issues need to be addressed to
1728 ensure that cryptography is used properly.

1729 This section identifies issues to be addressed after determining that cryptography is
1730 required for an application.

6.1   Required Security Strength

1732 The minimum security strength is determined by the sensitivity level of the information
1733 (see FIPS 199). SP 800-152 requires a security strength of at least 112 bits for the protection
1734 of Low-impact information, 128 bits for Moderate-impact information, and 192 bits for
1735 High-impact information. The required security strength can then be used to determine the
1736 algorithm and key size to be used. Section 5.6 of SP 800-57, Part 1 provides tables for
1737 selecting appropriate algorithms and key sizes.

1738 Many applications require the use of several different cryptographic algorithms. Ideally,
1739 these algorithms would all offer the same security strength, but this may not always be the
1740 case for performance, availability and interoperability reasons. When algorithms of
1741 different strengths are used together to protect data, the security provided by the
1742 combination of algorithms is the strength associated with the algorithm with the lowest
1743 security strength (see Section 5.6 of SP 800-57, Part 1). For example, RSA with 2048-bit
1744 keys can support a security strength of 112 bits, but is often used with SHA-256, which
1745 can support a security strength of 128 bits. When the combination is used to generate a
1746 digital signature, the signature can only provide a security strength of 112 bits – the lesser
1747 strength offered by the two algorithms.

1748 **Approved** combinations of algorithms (called cipher suites) for some of the protocols are
1749 provided in SP 800-57, Part 3 (for S/MIME) and SP 800-52 (for TLS).

6.2   Interoperability

1751 Interoperability is the ability of one entity to communicate with another entity, whether the
1752 entities are people, devices or processes. In order to communicate, the entities must have:

1753 • A communications channel (e.g., the Internet) and the same communications
1754   protocol (e.g., TLS), and

1755 • Policies that allow the entities to communicate.

1756 In order to communicate securely, the entities must also have:

1757 • Trust that each entity will enforce its own policies.

1758 • Interoperable cryptographic capabilities as discussed in Section 4, and

1759   • Share appropriate keying material that has been established securely (see Section
1760   5.3).

1761   For example, if entities A and B are in two different organizations, and

1762   • Each organization has a policy that allows the entities to communicate,

1763   • Each entity trusts that the other entity will enforce its own policies,

1764   • There is a TLS capability that can be used for communication,

1765   • Each entity can encrypt and decrypt information using AES with a 128-bit key and
1766   establish keys using 3072-bit RSA key transport (see Section 5.3.4.1), and

1767   • One of the entities can generate a 128-bit AES key and act as the sender in the key-
1768   transport scheme, and the other entity has a 3072-bit RSA key pair and can act as
1769   the receiver,

1770   then the two entities have a secure and interoperable communication channel that can be
1771   used to establish a 128-bit key for encrypting information using AES. In this case, the
1772   security strength that can be provided by an encryption operation using AES is 128 bits,
1773   since both 3072-bit RSA and AES-128 are rated at a security strength of 128 bits (see
1774   Section 6.1).

6.3   When Algorithms are No Longer Approved

1776   In the case that an algorithm is **no longer approved** for providing adequate protection (e.g.,
1777   the algorithm may have been "broken"), a risk assessment needs to be performed to
1778   determine whether the information should be re-protected using an **approved** algorithm
1779   and key size that will protect the information for the remainder of its security life. See
1780   Section 5.6.4 for SP 800-57, Part 1 for additional discussion.

6.4   Registration Authorities (RAs)

1782   As discussed in Section 5.2.3.1, an RA verifies the identity of users applying for a
1783   certificate and authenticates other information to be included in a certificate generated by
1784   a Certification Authority (CA). The correctness of this information is the linchpin on which
1785   the security of using certificates is based. Once this information is verified, the appropriate
1786   information is submitted to a CA for certificate generation using a signed certification
1787   request. The security of the certificate generation process requires that the CA only
1788   generate certificates for RAs that it trusts to have:

1789   • Verified the identity of the entity requesting a certificate and the authorization of
1790   that entity to obtain a certificate;

1791   • Checked that the information submitted for inclusion in the certificate is valid (e.g.,
1792   the public key is valid, and the private key is in the possession of the key pair's
1793   owner[84]); and

---

[84] The entity requesting the certificate may not be the key pair's owner. Compare the definitions of the
owner of a key pair and the owner of a certificate in Section 1.5.

1794   • Provided (and continues to provide) adequate protection for the private key used to
1795   sign the certification request.

6.5   Cross Certification

1797 Cross certification is the establishment of a trust relationship between two Certification
1798 Authorities (CAs) through the signing of each other's public key in a certificate referred to
1799 as a "cross-certificate." Cross-certificates provide a means to create a chain of trust from a
1800 single, trusted, root CA to multiple other CAs so that subscribers in one CA domain can
1801 interact safely with subscribers in other CA domains (e.g., the subscriber in one CA domain
1802 has assurance of the identity of the subscriber in the other domain and assurance of the
1803 accurateness of the other information provided by his certificate).

1804 Cross certification should only be performed when each CA examines the other CA's
1805 policies, finds them acceptable and trusts that CA to operate in accordance with those
1806 policies.

1807   Appendix A: References

1808   The following FIPS and NIST Special Publications (SP) apply to the use of cryptography
1809   in the Federal Government.

FIPS 140	National Institute of Standards and Technology (2019) Security Requirements for Cryptographic Modules. (U.S. Department of Commerce, Washington, D.C.), Federal Information Processing Standards Publication (FIPS) 140-3. https://doi.org/10.6028/NIST.FIPS.140-3
	FIPS 140-3 specifies the requirements that must be met by cryptographic modules protecting U.S. Government information. The standard provides four increasing, qualitative levels of security. The security requirements cover areas related to the secure design and implementation of a cryptographic module.
FIPS 180	National Institute of Standards and Technology (2015) Secure Hash Standard (SHS). (U.S. Department of Commerce, Washington, D.C.), Federal Information Processing Standards Publication (FIPS) 180-4. https://doi.org/10.6028/NIST.FIPS.180-4
	FIPS 180-4 specifies seven cryptographic hash algorithms: SHA-1, SHA-224, SHA-256, SHA-384, SHA-512, SHA-512/224 and SHA-512/256.
FIPS 185	National Institute of Standards and Technology (1994), Escrowed Encryption Standard, (U.S. Department of Commerce, Washington, D.C.), Federal Information Processing Standards Publication (FIPS) 185. Withdrawn October 19, 2015. https://csrc.nist.gov/CSRC/media/Publications/fips/185/archive/1994-02-09/documents/fips185.pdf
	FIPS 185 specified the use of an encryption/decryption algorithm and a Law Enforcement Access Field (LEAF) creation method that could be implemented in electronic devices and used for protecting government telecommunications when such protection was desired. The algorithm and the LEAF creation method were classified. The LEAF was intended for use in a key escrow system that provided for the decryption of telecommunications when access to the telecommunications was lawfully authorized.
FIPS 186	National Institute of Standards and Technology (2013) Digital Signature Standard (DSS). (U.S. Department of Commerce, Washington, D.C.), Federal Information Processing Standards Publication (FIPS) 186-4. https://doi.org/10.6028/NIST.FIPS.186-4

	FIPS 186-4 specifies a suite of algorithms that can be used to generate a digital signature: DSA, ECDSA, EdDSA and RSA. This Standard includes methods for the generation of digital signatures, methods for the generation of domain parameters (for DSA, ECDSA and EdDSA), and methods for the generation of key pairs, and requires certain assurances for using digital signatures: assurance of domain-parameter validity (DSA, ECDSA and EdDSA), and assurance of public-key validity and assurance of private-key possession for all three algorithms.
FIPS 197	National Institute of Standards and Technology (2001) Advanced Encryption Standard (AES). (U.S. Department of Commerce, Washington, D.C.), Federal Information Processing Standards Publication (FIPS) 197. https://doi.org/10.6028/NIST.FIPS.197 FIPS 197 specifies a symmetric key block cipher algorithm. The Standard supports key sizes of 128, 192, and 256 bits and a block size of 128 bits.
FIPS 198	National Institute of Standards and Technology (2008) The Keyed-Hash Message Authentication Code (HMAC). (U.S. Department of Commerce, Washington, D.C.), Federal Information Processing Standards Publication (FIPS) 198-1. https://doi.org/10.6028/NIST.FIPS.198-1 FIPS 198-1 defines a message authentication code (MAC) that uses a cryptographic hash function in conjunction with a secret key for the calculation and verification of the MAC.
FIPS 199	National Institute of Standards and Technology (2004) Standards for Security Categorization of Federal Information and Information Systems. (U.S. Department of Commerce, Washington, D.C.), Federal Information Processing Standards Publication (FIPS) 199. https://doi.org/10.6028/NIST.FIPS.199 FIPS 199 establishes security categories for both information and information systems. The security categories are based on the potential impact on an organization if certain events occur that jeopardize the information and information systems needed by the organization to accomplish its assigned mission, protect its assets, fulfill its legal responsibilities, maintain its day-to-day functions, and protect individuals.
FIPS 202	National Institute of Standards and Technology (2015) SHA-3 Standard: Permutation-Based Hash and Extendable-Output Functions.

	(U.S. Department of Commerce, Washington, D.C.), Federal Information Processing Standards Publication (FIPS) 202. https://doi.org/10.6028/NIST.FIPS.202
	FIPS 202 specifies SHA3-224, SHA3-256, SHA3-384 and SHA3-512. This FIPS also specifies two extendable-output functions (SHAKE128 and SHAKE256), which are not, in themselves, considered to be hash functions.
SP 800-22	Bassham LE, III, Rukhin A, Soto J, Nechvatal JR, Smid ME, Barker EB, Leigh SD, Levenson M, Vangel M, Banks D, Heckert NA, Dray JF, Jr. (2010) A Statistical Test Suite for Random and Pseudorandom Number Generators for Cryptographic Applications. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Special Publication (SP) 800-22, Rev. 1a. https://doi.org/10.6028/NIST.SP.800-22r1a
	SP 800-22 discusses some aspects of selecting and testing random and pseudorandom number generators for providing random numbers that are indistinguishable from truly random output.
SP 800-32	Kuhn R, Hu VC, Polk T, Chang S-jH (2001) Introduction to Public Key Technology and the Federal PKI Infrastructure. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Special Publication (SP) 800-32. https://doi.org/10.6028/NIST.SP.800-32
	SP 800-32 was developed to assist agency decision-makers in determining if a PKI is appropriate for their agency, and how PKI services can be deployed most effectively within a Federal agency. It is intended to provide an overview of PKI functions and their applications.
SP 800-38	A series of publications specifying modes of operation for block cipher algorithms (see below).
SP 800-38A	Dworkin MJ (2001) Recommendation for Block Cipher Modes of Operation: Methods and Techniques. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Special Publication (SP) 800-38A. https://doi.org/10.6028/NIST.SP.800-38A
	SP 800-38A defines five confidentiality modes of operation for use with an underlying symmetric key block cipher algorithm: Electronic Codebook (ECB), Cipher Block Chaining (CBC), Cipher Feedback (CFB), Output Feedback (OFB), and Counter (CTR). Used with an **approved** underlying block cipher algorithm (i.e., AES or TDEA),

	these modes can provide cryptographic protection for sensitive computer data.
SP 800-38B	Dworkin MJ (2005) Recommendation for Block Cipher Modes of Operation: the CMAC Mode for Authentication. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Special Publication (SP) 800-38B, Includes updates as of October 6, 2016. https://doi.org/10.6028/NIST.SP.800-38B
	SP 800-38B specifies a message authentication code (MAC) algorithm based on a symmetric key block cipher (i.e., AES or TDEA). This block cipher-based MAC algorithm, called CMAC, may be used to provide assurance of the source and integrity of binary data.
SP 800-38C	Dworkin MJ (2004) Recommendation for Block Cipher Modes of Operation: the CCM Mode for Authentication and Confidentiality. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Special Publication (SP) 800-38C, Includes updates as of July 20, 2007. https://doi.org/10.6028/NIST.SP.800-38C
	SP 800-38C defines a mode of operation, called CCM, for a symmetric-key block cipher algorithm with a 128-bit block size (i.e., AES). CCM may be used to provide assurance of the confidentiality and the authenticity of computer data by combining the techniques of the Counter (CTR) mode specified in SP 800-38A, and the Cipher Block Chaining-Message Authentication Code (CBC-MAC) algorithm (specified in SP 800-90B, but **not** currently approved for general use)
SP 800-38D	Dworkin MJ (2007) Recommendation for Block Cipher Modes of Operation: Galois/Counter Mode (GCM) and GMAC. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Special Publication (SP) 800-38D. https://doi.org/10.6028/NIST.SP.800-38D
	SP 800-38D specifies the Galois/Counter Mode (GCM), an algorithm for authenticated encryption with associated data, and its specialization, GMAC, for generating a message authentication code (MAC) on data that is not encrypted. GCM and GMAC are modes of operation for an underlying, **approved** symmetric-key block cipher with a 128-bit block size (i.e., AES).
SP 800-38E	Dworkin MJ (2010) Recommendation for Block Cipher Modes of Operation: the XTS-AES Mode for Confidentiality on Storage Devices. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Special Publication (SP) 800-38E. https://doi.org/10.6028/NIST.SP.800-38E

	SP 800-38E approves the XTS-AES mode of the AES algorithm by reference to IEEE 1619, subject to one additional requirement, as an option for protecting the confidentiality of data on storage devices. The mode does not provide authentication of the data or its source.
SP 800-38F	Dworkin MJ (2012) Recommendation for Block Cipher Modes of Operation: Methods for Key Wrapping. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Special Publication (SP) 800-38F. https://doi.org/10.6028/NIST.SP.800-38F
	SP 800-38F describes cryptographic methods that are approved for key wrapping. In addition to approving existing methods, this publication specifies two new, deterministic authenticated-encryption modes of operation of the Advanced Encryption Standard (AES) algorithm: the AES Key Wrap (KW) mode and the AES Key Wrap with Padding (KWP) mode. An analogous mode with the Triple Data Encryption Algorithm (TDEA) as the underlying block cipher, called TKW, is also specified to support legacy applications.
SP 800-38G	Dworkin MJ (2012) Recommendation for Block Cipher Modes of Operation: Methods for Key Wrapping. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Special Publication (SP) 800-38F. https://doi.org/10.6028/NIST.SP.800-38F
	SP 800-38G specifies methods for format-preserving encryption, called FF1 and FF3. Each of these methods is a mode of operation of the AES algorithm, which is used to construct a round function within the Feistel structure for encryption.
SP 800-52	Polk T, McKay KA, Chokhani S (2014) Guidelines for the Selection, Configuration, and Use of Transport Layer Security (TLS) Implementations. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Special Publication (SP) 800-52, Rev. 1. https://doi.org/10.6028/NIST.SP.800-52r1
	Transport Layer Security (TLS) provides mechanisms to protect sensitive data during electronic dissemination across the Internet. SP 800-52 provides guidance about the selection and configuration of TLS protocol implementations, while making effective use of Federal Information Processing Standards (FIPS) and NIST-recommended cryptographic algorithms (specified in SPs), and requires that TLS 1.1 be configured with FIPS-based cipher suites as the minimum appropriate secure transport protocol. This publication also identifies TLS extensions for which mandatory support must be provided and identifies other recommended extensions.

SP 800-53	Joint Task Force Transformation Initiative (Draft 2013) Security and Privacy Controls for Federal Information Systems and Organizations. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Special Publication (SP) 800-53, Rev. 5, Draft updated August 2017 https://csrc.nist.gov/CSRC/media//Publications/sp/800-53/rev-5/draft/documents/sp800-53r5-draft
	SP 800-53 provides a catalog of security and privacy controls for federal information systems and organizations, and a process for selecting controls to protect organizational operations (including mission, functions, image, and reputation), organizational assets, individuals, other organizations, and the Nation from a diverse set of threats, including hostile cyber attacks, natural disasters, structural failures, and human errors.
SP 800-56A	Barker EB, Chen L, Roginsky A, Vassilev A, Davis R (2018) Recommendation for Pair-Wise Key-Establishment Schemes Using Discrete Logarithm Cryptography. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Special Publication (SP) 800-56A, Rev. 3. https://doi.org/10.6028/NIST.SP.800-56Ar3
	SP 800-56A specifies key-establishment schemes based on the discrete logarithm problem over finite fields and elliptic curves, including several variations of Diffie-Hellman and Menezes-Qu-Vanstone (MQV) key-establishment schemes.
SP 800-56B	Barker EB, Chen L, Roginsky A, Vassilev A, Davis R, Simon S (2019) Recommendation for Pair-Wise Key-Establishment Using Integer Factorization Cryptography. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Special Publication (SP) 800-56B, Rev. 2. https://doi.org/10.6028/NIST.SP.800-56Br2
	SP 800-56B specifies key-establishment schemes using integer-factorization cryptography (RSA). Both key transport and key-agreement schemes are specified.
SP 800-56C	Barker EB, Chen L, Davis R (2018) Recommendation for Key-Derivation Methods in Key-Establishment Schemes. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Special Publication (SP) 800-56C, Rev. 1. https://doi.org/10.6028/NIST.SP.800-56Cr1
	SP 800-56C specifies techniques for the derivation of keying material from a shared secret established during a key-establishment scheme

	defined in SP 800-56A or SP 800-56B through an extraction-then-expansion procedure.
SP 800-57, Part 1	Barker EB (2016) Recommendation for Key Management, Part 1: General. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Special Publication (SP) 800-57 Part 1, Rev. 4. https://doi.org/10.6028/NIST.SP.800-57pt1r4 Part 1 of SP 800-57 provides general guidance and best practices for the management of cryptographic keying material. It focuses on issues involving the management of cryptographic keys: their generation, use, and eventual destruction. Related topics, such as algorithm selection and appropriate key size, cryptographic policy, and cryptographic module selection, are also included.
SP 800-57, Part 2	Barker EB, Barker WC (2019) Recommendation for Key Management: Part 2 – Best Practices for Key Management Organizations. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Special Publication (SP) 800-57 Part 2, Rev. 1. https://doi.org/10.6028/NIST.SP.800-57pt2r1 Part 2 of SP 800-57 provides guidance on policy and security planning requirements for U.S. government agencies. This part of SP 800-57 contains a generic key-management infrastructure, guidance for the development of organizational key-management policy statements and key-management practices statements, an identification of key-management information that needs to be incorporated into security plans for general support systems and major applications that employ cryptography, and an identification of key-management information that needs to be documented for all Federal applications of cryptography.
SP 800-57, Part 3	Barker EB, Dang QH (2015) Recommendation for Key Management, Part 3: Application-Specific Key Management Guidance. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Special Publication (SP) 800-57 Part 3, Rev. 1. https://doi.org/10.6028/NIST.SP.800-57pt3r1 Part 3 of SP 800-57 addresses the key-management issues associated with currently available cryptographic mechanisms, such as the Public Key infrastructure (PKI), Internet Protocol Security (IPsec), Secure/Multipart Internet Mail Extensions (S/MIME), Kerberos, Over-the-Air Rekeying (OTAR), Domain Name System Security Extensions (DNSSEC), Encrypted File Systems and the Secure Shell (SSH) protocol.

SP 800-67	Barker EB, Mouha N (2017) Recommendation for the Triple Data Encryption Algorithm (TDEA) Block Cipher. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Special Publication (SP) 800-67, Rev. 2. https://doi.org/10.6028/NIST.SP.800-67r2
	SP 800-67 specifies the Triple Data Encryption Algorithm (TDEA), including its primary component cryptographic engine, the Data Encryption Algorithm (DEA).
SP 800-71	Barker EB, Barker WC (Draft 2018), Recommendation for Key Establishment Using Symmetric Block Ciphers. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Special Publication (SP) 800-71. https://csrc.nist.gov/CSRC/media/Publications/sp/800-71/draft/documents/sp800-71-draft.pdf
	SP 800-71 addresses the protection of symmetric keying material during a key establishment that uses symmetric-key cryptography for key distribution. The Recommendation also addresses recovery in the event of detectable errors during the key-distribution process. Wrapping mechanisms are specified for encrypting keys, binding key control information to the keys and protecting the integrity of this information.
SP 800-89	Barker EB (2006) Recommendation for Obtaining Assurances for Digital Signature Applications. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Special Publication (SP) 800-89. https://doi.org/10.6028/NIST.SP.800-89
	Entities participating in the generation or verification of digital signatures depend on the authenticity of the process. SP 800-89 specifies methods for obtaining the assurances necessary for valid digital signatures: assurance of domain parameter validity, assurance of public key validity, assurance that the key-pair owner actually possesses the private key, and assurance of the identity of the key pair owner.
SP 800-90A	Barker EB, Kelsey JM (2015) Recommendation for Random Number Generation Using Deterministic Random Bit Generators. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Special Publication (SP) 800-90A, Rev. 1. https://doi.org/10.6028/NIST.SP.800-90Ar1
	SP 800-90A specifies DRBG mechanisms for the generation of random bits using deterministic methods. The methods provided are based on either hash functions or block cipher algorithms and are designed to support selected security strengths. DRBGs must be

	initialized from a randomness source that provides sufficient entropy for the security strength to be supported by the DRBG.
SP 800-90B	Sönmez Turan M, Barker EB, Kelsey JM, McKay KA, Baish ML, Boyle M (2018) Recommendation for the Entropy Sources Used for Random Bit Generation. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Special Publication (SP) 800-90B. https://doi.org/10.6028/NIST.SP.800-90B
	SP 800-90B specifies the design principles and requirements for the entropy sources used by Random Bit Generators, including health tests to determine that the entropy source has not failed and tests for the validation of entropy sources.
SP 800-90C	Barker EB, Kelsey JM (Draft 2016), Recommendation for Random Bit Generator (RBG) Constructions. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Special Publication (SP) 800-90C. http://csrc.nist.gov/publications/PubsSPs.html#800-90C
	SP 800-90C specifies constructions for the implementation of random bit generators (RBGs). An RBG may be a deterministic random bit generator (DRBG) or a non-deterministic random bit generator (NRBG). The constructed RBGs consist of DRBG mechanisms as specified SP 800-90A and entropy sources as specified in SP 800-90B.
SP 800-102	Barker EB (2009) Recommendation for Digital Signature Timeliness. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Special Publication (SP) 800-102. https://doi.org/10.6028/NIST.SP.800-102
	Establishing the time when a digital signature was generated is often a critical consideration. A signed message that includes the (purported) signing time provides no assurance that the private key was used to sign the message at that time unless the accuracy of the time can be trusted. With the appropriate use of digital signature-based timestamps from a Trusted Timestamp Authority and/or verifier-supplied data that is included in the signed message, the signer can provide some level of assurance about the time that the message was signed.
SP 800-106	Dang QH (2009) Randomized Hashing for Digital Signatures. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Special Publication (SP) 800-106. https://doi.org/10.6028/NIST.SP.800-106
	NIST-approved digital signature algorithms require the use of an **approved** cryptographic hash function in the generation and verification of signatures. SP 800-106 specifies a method to enhance

	the security of the cryptographic hash functions used in digital signature applications by randomizing the messages that are signed.
SP 800-107	Dang QH (2012) Recommendation for Applications Using Approved Hash Algorithms. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Special Publication (SP) 800-107, Rev. 1. https://doi.org/10.6028/NIST.SP.800-107r1
	Hash functions that compute a fixed-length message digest from arbitrary length messages are widely used for many purposes in information security. SP 800-107 provides security guidelines for achieving the required or desired security strengths when using cryptographic applications that employ the approved hash functions specified in FIPS 180. These include functions such as digital signatures, Keyed-hash Message Authentication Codes (HMACs) and Hashed-based Key Derivation Functions (hash-based KDFs).
SP 800-108	Chen L (2009) Recommendation for Key Derivation Using Pseudorandom Functions (Revised). (National Institute of Standards and Technology, Gaithersburg, MD), NIST Special Publication (SP) 800-108, Revised. https://doi.org/10.6028/NIST.SP.800-108
	SP 800-108 specifies techniques for the derivation of additional keying material from a secret key (i.e., a key-derivation key) using pseudorandom functions. The key-derivation key may have been either established through a key-establishment scheme or shared through some other manner (e.g., a manual key distribution).
SP 800-130	Barker EB, Smid ME, Branstad DK, Chokhani S (2013) A Framework for Designing Cryptographic Key Management Systems. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Special Publication (SP) 800-130. https://doi.org/10.6028/NIST.SP.800-130
	SP 800-130 contains topics to be considered by a CKMS designer when developing a CKMS design specification. Topics include security policies, cryptographic keys and metadata, interoperability and transitioning, security controls, testing and system assurances, disaster recovery, and security assessments.
SP 800-131A	Barker EB, Roginsky A (2019) Transitioning the Use of Cryptographic Algorithms and Key Lengths. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Special Publication (SP) 800-131A, Rev. 2. https://doi.org/10.6028/NIST.SP.800-131Ar2
	Section 5.6.4 of SP 800-57, Part 1 provides recommendations for transitioning to new cryptographic algorithms and key lengths because

	of algorithm breaks or the availability of more powerful computers that could be used to efficiently search for cryptographic keys. SP 800-131A offers more specific guidance for such transitions. Each algorithm and service is addressed in SP 800-131A, indicating whether its use is acceptable, deprecated, restricted, allowed only for legacy applications[85], or disallowed.
SP 800-132	Sönmez Turan M, Barker EB, Burr WE, Chen L (2010) Recommendation for Password-Based Key Derivation: Part 1: Storage Applications. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Special Publication (SP) 800-132. https://doi.org/10.6028/NIST.SP.800-132 SP 800-132 specifies techniques for the derivation of master keys from passwords or passphrases to protect stored electronic data or data protection keys.
SP 800-133	Barker EB, Roginsky A (2012) Recommendation for Cryptographic Key Generation. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Special Publication (SP) 800-133. https://doi.org/10.6028/NIST.SP.800-133 SP 800-133 discusses the generation of the keys to be managed and used by the **approved** cryptographic algorithms.
SP 800-135	Dang QH (2011) Recommendation for Existing Application-Specific Key Derivation Functions. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Special Publication (SP) 800-135, Rev. 1. https://doi.org/10.6028/NIST.SP.800-135r1 Many widely-used internet security protocols have their own application-specific Key Derivation Functions (KDFs) that are used to generate the cryptographic keys required for their cryptographic functions. SP 800-135 provides security requirements for those KDFs.
SP 800-152	Barker EB, Branstad DK, Smid ME (2015) A Profile for U.S. Federal Cryptographic Key Management Systems (CKMS). (National Institute of Standards and Technology, Gaithersburg, MD), NIST Special Publication (SP) 800-152. https://doi.org/10.6028/NIST.SP.800-152 SP 800-152 contains requirements for the design, implementation, procurement, installation, configuration, management, operation and use of a CKMS by and for U.S. federal organizations and their

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[85] The algorithm and key length may be used to process already-protected information, but there may be a risk in doing so.

	contractors. The Profile is based on NIST Special Publication SP 800-130.
SP 800-175A	Barker EB, Barker WC (2016) Guideline for Using Cryptographic Standards in the Federal Government: Directives, Mandates and Policies. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Special Publication (SP) 800-175A. https://doi.org/10.6028/NIST.SP.800-175A
	SP 800-175A provides guidance on the determination of requirements for using cryptography. It includes a summary of laws and regulations concerning the protection of the Federal Government's sensitive information, guidance regarding the conduct of risk assessments to determine what needs to be protected and how best to protect that information, and a discussion of the relevant security-related documents (e.g., various policy and practice documents).
SP 800-185	Kelsey JM, Chang S-jH, Perlner RA (2016) SHA-3 Derived Functions: cSHAKE, KMAC, TupleHash, and ParallelHash. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Special Publication (SP) 800-185. https://doi.org/10.6028/NIST.SP.800-185
	This Recommendation specifies four types of SHA-3- derived functions: cSHAKE, KMAC, TupleHash, and ParallelHash, each defined for a 128- and 256-bit security strength. cSHAKE is a customizable variant of the SHAKE function, as defined in Federal Information Processing Standard (FIPS) 202. KMAC (for KECCAK Message Authentication Code) is a variable-length message authentication code algorithm based on KECCAK; it can also be used as a pseudorandom function. TupleHash is a variable-length hash function designed to hash tuples of input strings without trivial collisions. ParallelHash is a variable-length hash function that can hash very long messages in parallel.
SP 800-186	Chen L, Moody D, Regenscheid A (2019 Draft) Recommendatio for Discrete-Logarithm Based Cryptography: Elliptic Curve Domain Parameters. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Special Publication (SP) 800-186. [Insert URL]
	This Recommendation contains the set of elliptic curves recommended for U.S. Government use.
NISTIR 7924	Booth H, Regenscheid A (2014) Reference Certificate Policy. (National Institute of Standards and Technology, Gaithersburg, MD), Draft (2nd) NIST Internal Report (NISTIR) 7924. Available at https://csrc.nist.gov/publications/detail/nistir/7924/draft

	NIST 7924 is intended to identify a set of security controls and practices to support the secure issuance of certificates. It was written in the form of a Certificate Policy (CP), a standard format for defining the expectations and requirements of the relying party community that will trust the certificates issued by its Certificate Authorities (CAs).

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1811　Non-NIST Publications:

IEEE 802.11	Institute of Electrical and Electronics Engineers, *Wireless Local Area Networks*, IEEE 802.11, August 2018. Available at https://ieeexplore.ieee.org/document/8457463
IEEE P1363	Institute of Electrical and Electronics Engineers, *Standard Specifications for Public-Key Cryptography*, IEEE P1363. Available at https://standards.ieee.org/standard/1363-2000.html
IEEE P1363a	Institute of Electrical and Electronics Engineers, *Standard Specifications For Public Key Cryptography- Amendment 1: Additional Techniques*, IEEE P1363a, March 2004. Available at https://www.techstreet.com/ieee/standards/ieee-1363a-2004?gateway_code=ieee&vendor_id=2050&product_id=1183345
IEEE P1363.1	Institute of Electrical and Electronics Engineers, *Public-Key Cryptographic Techniques Based on Hard Problems over Lattices*, IEEE P1363.1, October 2008. Available at https://www.techstreet.com/ieee/standards/ieee-1363-1-2008?gateway_code=ieee&vendor_id=3074&product_id=1744326
IEEE P1363.2	Institute of Electrical and Electronics Engineers, *Password-Based Public-Key Cryptography*, IEEE P1363-2, September2008. Available at https://www.techstreet.com/ieee/standards/ieee-1363-2-2008?gateway_code=ieee&vendor_id=4376&product_id=1613786
IEEE P1619	Institute of Electrical and Electronics Engineers, *Standard for Cryptographic Protection of Data on Block-Oriented Storage Devices*, IEEE P1619, (multiple parts), 2008. Available at https://www.techstreet.com/ieee/standards/ieee-1363-2-2008?gateway_code=ieee&vendor_id=4376&product_id=1613786
ISO/IEC 9594-8	International Organization for Standardization/International Electrotechnical Commision, *Information technology - Open Systems Interconnection - The Directory: Public-key and attribute certificate frameworks*, ITU-T Recommendation X.509, October 2016 (available at

	https://www.itu.int/itu-t/recommendations/rec.aspx?rec=X.509) and ISO/IEC 9594-8:2017, May 2017. (available at https://www.iso.org/standard/72557.html)
ISO/IEC 9797-1	International Organization for Standardization/International Electrotechnical Commision, *Information technology − Security techniques − Message Authentication Codes (MACs) − Part 1: Mechanisms using a block cipher,* ISO/IEC 9797-1:2011, March 2011. Available at https://www.iso.org/standard/50375.html This standard includes CMAC, as specified in SP 800-38B.
ISO/IEC 9797-2	International Organization for Standardization/International Electrotechnical Commision, *Information technology − Security techniques − Message Authentication Codes (MACs) − Part 2: Mechanisms using a dedicated hash-function*, ISO/IEC 9797-2:2011, May 2011. Available at https://www.iso.org/standard/51618.html This standard includes HMAC, as specified in FIPS 198.
ISO/IEC 10116	International Organization for Standardization/International Electrotechnical Commision, *Information technology − Security techniques − Modes of operation for an n-bit block cipher*, ISO/IEC 10116:2006, July 2017. Available at https://www.iso.org/standard/64575.html This standard includes all the modes specified in SP 800-38A.
ISO/IEC 10118-3	International Organization for Standardization/International Electrotechnical Commision, *Information technology − Security techniques − Hash-functions − Part 3: Dedicated hash-functions*, ISO/IEC 10118-3:2004, October 2018. Available at https://www.iso.org/standard/67116.html This standard includes SHA-1 and the SHA-2 family of hash functions specified in FIPS 180. A revision of ISO/IEC 10118-3 will include the SHA-3 functions specified in FIPS 202.
ISO/IEC 11770-3	International Organization for Standardization/International Electrotechnical Commision, *Information technology − Security techniques − Key management -- Part 3: Mechanisms using asymmetric techniques*, ISO/IEC 11770-3: 2015, August 2015. Available at https://www.iso.org/standard/60237.html

	This standard specifies key establishment mechanisms, some of which can be instantiated with key-establishment schemes specified in SP 800-56A and SP 800-56B.
ISO/IEC 11770-6	International Organization for Standardization/International Electrotechnical Commision, *Information technology − Security techniques − Key management − Part 6: Key derivation*, ISO/IEC 11770-6: 2016, October 2016. Available at https://www.iso.org/standard/65275.html This draft standard will include all key derivation functions specified in SP 800-108, as well as the two-step key derivation methods specified in SP 800-56C.
ISO/IEC 11889	International Organization for Standardization/International Electrotechnical Commision: *Information technology − Trusted Platform Module Library − Part 1: Architecture*, ISO/IEC 11889-1:2015, August 2015. Available at https://www.iso.org/standard/66510.html *Information technology − Trusted Platform Module − Part 2: Structures*, ISO/IEC 11889-2:2015, August 2015. Available at https://www.iso.org/standard/66511.html *Information technology − Trusted Platform Module − Part 3: Commands*, ISO/IEC 11889-3:2015, August 2015. Available at https://www.iso.org/standard/66512.html *Information technology − Trusted Platform Module Library − Part 4: Supporting Routines*, ISO/IEC 11889-4:2015, August 2015. Available at https://www.iso.org/standard/66513.html
ISO/IEC 14888-2	International Organization for Standardization/International Electrotechnical Commision, *Information technology − Security techniques − Digital signatures with appendix − Part 2: Integer factorization based mechanisms*, ISO/IEC 14888-2:2008, April 2008. Available at https://www.iso.org/standard/44227.html This standard includes RSA signatures, as specified in FIPS 186.
ISO/IEC 14888-3	International Organization for Standardization/International Electrotechnical Commision, *Information technology − Security techniques − Digital signatures with appendix − Part 3: Discrete logarithm based mechanisms*, ISO/IEC 14888-3:2018, November 2018. Available at

	https://www.iso.org/standard/76382.html This standard includes DSA, as specified for finite fields and elliptic curves in FIPS 186.
ISO/IEC 18033-3	International Organization for Standardization/International Electrotechnical Commision, *Information technology − Security techniques − Encryption algorithms − Part 3: Block ciphers,* ISO/IEC 18033-3:2010, December 2010. Available at https://www.iso.org/standard/54531.html This standard includes 64-bit block ciphers: TDEA, MISTY1, CAST-128, HIGHT and 128-bit block ciphers: AES, Camellia, and SEED. Note that TDEA is specified in SP 800-67 and AES is specified in FIPS 197.
ISO/IEC 19772	International Organization for Standardization/International Electrotechnical Commision, *Information technology − Security techniques − Authenticated encryption*, ISO/IEC 19772:2009, February 2009. Availabe at https://www.iso.org/standard/46345.html This standard includes CCM (as specified in SP 800-38C), GCM (as specified in SP 800-38D), and Key wrapping (as specified in SP 800-38E).
PKCS 1	Moriarty K (ed.), Kaliski B, Jonsson J, Rush A (2016) *PKCS #1: RSA Cryptography Specifications Version 2.2.* (Internet Engineering Task Force), IETF Request for Comments (RFC) 8017. https://doi.org/10.17487/RFC8017 PKCS 1 provides recommendations for the implementation of public-key cryptography based on the RSA algorithm, covering cryptographic primitives, encryption schemes, signature schemes with appendix and the ASN.1 syntax for representing keys and for identifying the schemes.
RFC 3526	*More Modular Exponential (MODP) Diffie-Hellman groups for Internet Key Exchange (IKE)*, Internet Engineering Task Force, Network Working Group, Request for Comments 3526, The Internet Society; May 2003. https://www.ietf.org/rfc/rfc3526.txt This document defines new Modular Exponential (MODP) Groups for the Internet Key Exchange (IKE) protocol.

RFC 5288	*AES Galois Counter Mode (GCM) Cipher Suites for TLS*, Internet Engineering Task Force, Network Working Group, Request for Comments 5288, The Internet Society; August 2008. https://tools.ietf.org/html/rfc5288
	This RFC describes the use of the Advanced Encryption Standard (AES)in Galois/Counter Mode (GCM) as a Transport Layer Security (TLS)authenticated encryption operation.
RFC 7919	*Negotiated Finite Field Diffie-Hellman Ephemeral Parameters for Transport Layer Security (TLS)*, Internet Engineering Task Force, Network Working Group, Request for Comments 7919, The Internet Society; August 2016. https://tools.ietf.org/html/rfc7919
	This document establishes finite field DH parameters with known structure.
RFC 8017	*RSA Cryptography Specifications Version 2.2*, Internet Engineering Task Force, Network Working Group, Informational RFC 8017, The Internet Society; November 2016. https://tools.ietf.org/html/rfc8017
	This document provides recommendations for the implementation of public-key cryptography based on the RSA algorithm, covering cryptographic primitives, encryption schemes, signature schemes with appendix, and ASN.1 syntax for representing keys and for identifying the schemes.
RFC 8032	*Edwards Curve Digital Signature Algorithm*, Internet Engineering Task Force, Network Working Group, Request for Comments 8032, The Internet Society; January 2017. https://tools.ietf.org/html/rfc8032
	This document describes elliptic curve signature scheme Edwards-curve Digital Signature Algorithm (EdDSA).

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Appendix B: Revisions

In 2018, the following changes were made to the original (2015) version of this document.

1. Section 1.1: Added an alternative term "integrity verification" to bullet 1. Added "integrity authentication to the bulleted list.

2. Section 1.5: Made changes to the following terms: authentication, compromise, confidentiality, keying material, mode of operation, plaintext, secret key, source authentication, symmetric key, symmetric-key (secret) algorithm.

   Added the following terms: domain parameters, identity authentication, integrity authentication, key information, key wrapping, metadata, owner of a certificate, owner of a key or key pair, pre-shared key, protocol, scheme, security function, server.

3. Section 1.6: Added the following acronyms: KMAC, OMB, ROTs, TPM.

4. Section 1.7: Changed the summary of Section 4.

5. Section 2.2.2: Added a sentence about the prohibition of waivers.

6. Section 2.3.4: Removed the dates from the list of ISO Standards.

7. Section 3.1: Added SP 800-185 to the list of documents containing approved hash functions. Added text to explain the nomenclature for the SHA functions and a bullet for SP 800-185.

8. Section 3.2.1.2: Revised to agree with the strategy for deprecating and/or disallowing the use of 2-key and 3-key TDEA.

9. Section 3.2.1.4: Added text to explain the nomenclature used for AES and its acceptability.

10. Section 3.2.1.5: Revised para. 1 to explain why modes are needed.

11. Section 3.2.2: Added a paragraph about SP 800-185.

12. Section 3.3: Revised the text about the use of asymmetric-key algorithms. Added a note about post-quantum algorithms and why they are needed in the future.

13. Section 3.3.1: Added a general discussion of digital signature algorithms.

14. Section 3.3.1.2: Inserted text that indicates that the elliptic curves will be provided in SP 800-186 rather than in FIPS 186. Changed the last paragraph about the contents of the revision of FIPS 186.

15. Section 3.3.1.3: A new section about EdDSA which is specified in the latest revision of FIPS 186.

16. Section 3.3.1.4: This section has been revised to discuss the RSA of RSA for digital signatures and to be consistent with FIPS 186-5.

17. Section 3.3.2: New introductory material on key-establishment schemes has been added.

18. Section 3.3.2.1: This section has been revised.

19. Section 3.3.2.2: Added material from Section 3.3 of the previous version to specifically discussed the use of RSA for key establishment.

20. Section 3.4: Added text to the end of the third paragraph about accepting the risks of using keys that provide only 80 bits of security.

21. Section 4.1: Added a sentence at the end of para. 1 that warns the reader about the deprecation of three-key TDEA.

22. Section 4.2: Added text about the use of integrity codes at the end of the first paragraph. Inserted a paragraph about identity authentication and revised the paragraph about source authentication.

23. Section 4.2.2: Revised and reorganized this section on MAC algorithms.

24. Section 4.2.2.2: Added a paragraph about SP 800-185.

25. Section 4.2.3: Revised the steps describing the generation and verification of digital signatures (for easier understanding). Added EdDSA to the list of algorithms provided in FIPS 186-5.

26. Section 4.4: Revised the description of SP 800-90B.

27. Section 4.5: Revised the third paragraph to discuss key distribution. Added text to the end of the last paragraph warning about the advent of quantum computing.

28. Section 5.0: Added an explanation of the term "key information" as used in the document.

29. Section 5.1.1: Revised the description of the contents of SP 800-57, Part 2. Added a note that TLS is now discussed in SP 800-52.

30. Section 5.1.2: Provided a new link to the CMVP.

31. Section 5.2.3: Added EdDSA to the list of approved digital-signature algorithms. Revised a discussion of the use of public keys, relying parties, etc. (above the bulleted items).

32. Section 5.2.3.1, item 4: Added a recommendation for the inventory of all certificates. Expanded on a discussion of certificate expiration.

33. Section 5.3.2, last paragraph: Revised to indicate that the KDFs that were previously in SP 800-56A and SP 800-56B are now all in SP 800-56C.

34. Section 5.3.3. para. 2: All key-derivation methods for SP 800-56A and SP 800-56B are now in SP 800-56C.

35. Section 5.3.4: The description of SP 800-56B has been changed, and a reference to SP 800-71 has been added.

36. Section 5.3.4.1: The first paragraph has been shortened.

37. Section 5.3.4.2: This is a new section about SP 800-71.

38. Section5.4.1: A reference to SP 800-71 has been added.

39. Section 5.4.5: The links to the CAVP and CMVP have been updated.

1886   40. Section 5.4.8: This section on has been revised to include both accountability and key
1887   and certificate inventory management.

1888   41. Section 5.4.9: This is a new section on the different kinds of auditing.

1889   42. Section 6.4: Text discussing the security of the certificate generation process has been
1890   revised.

1891   43. Appendix A: The references have been updated.