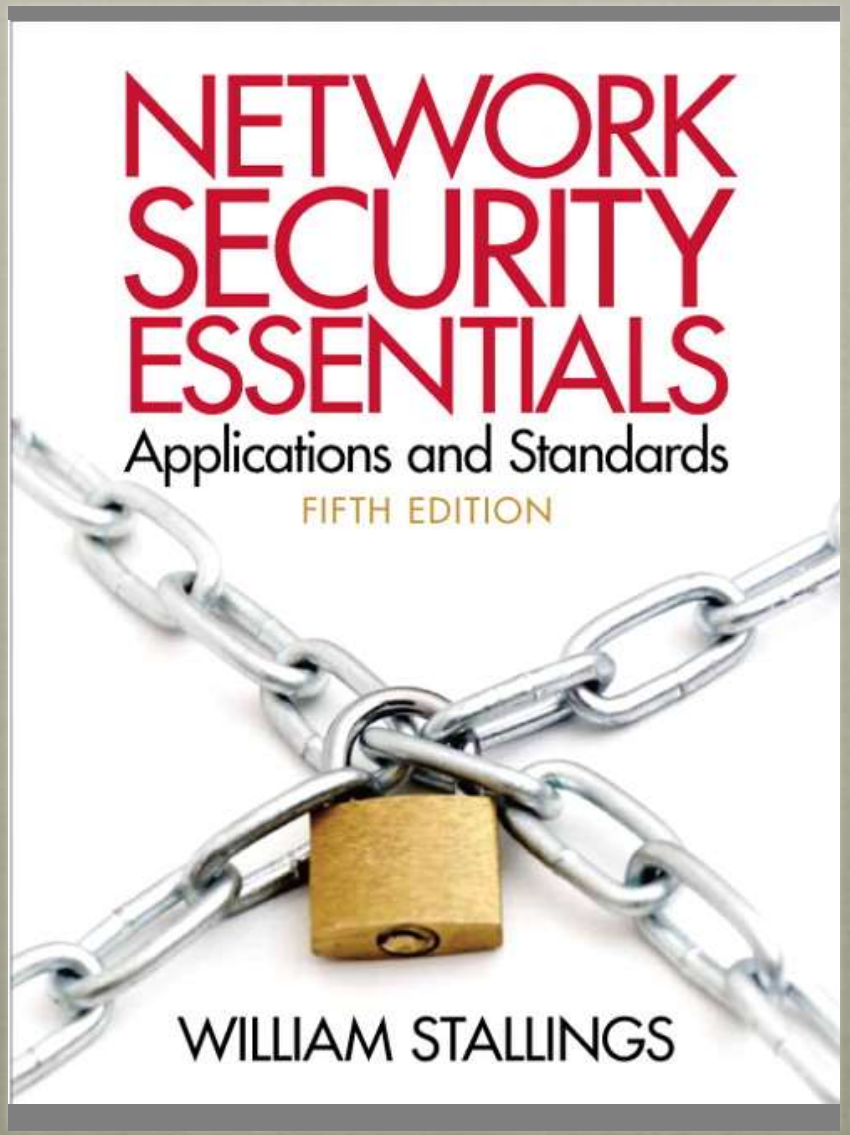
NETWORK SECURITY ESSENTIALS

Fifth Edition

by William Stallings



CHAPTER 3

Public Key Cryptography and Message Authentication

Every Egyptian received two names, which were known respectively as the true name and the good name, or the great name and the little name; and while the good or little name was made public, the true or great name appears to have been carefully concealed.

—***The Golden Bough,*** **Sir James George Frazer**

To guard against the baneful influence exerted by strangers is therefore an elementary dictate of savage prudence. Hence before strangers are allowed to enter a district, or at least before they are permitted to mingle freely with the inhabitants, certain ceremonies are often performed by the natives of the country for the purpose of disarming the strangers of their magical powers, or of disinfecting, so to speak, the tainted atmosphere by which they are supposed to be surrounded.

—***The Golden Bough,*** **Sir James George Frazer**

APPROACHES TO MESSAGE AUTHENTICATION

Using conventional encryption

- Symmetric encryption alone is not a suitable tool for data authentication
  - We assume that only the sender and receiver share a key, so only the genuine sender would be able to encrypt a message successfully
  - The receiver assumes that no alterations have been made and that sequencing is proper if the message includes an error detection code and a sequence number
  - If the message includes a timestamp, the receiver assumes that the message has not been delayed beyond that normally expected for network transit

Without message encryption

- An authentication tag is generated and appended to each message for transmission
- The message itself is not encrypted and can be read at the destination independent of the authentication function at the destination
- Because the message is not encrypted, message confidentiality is not provided

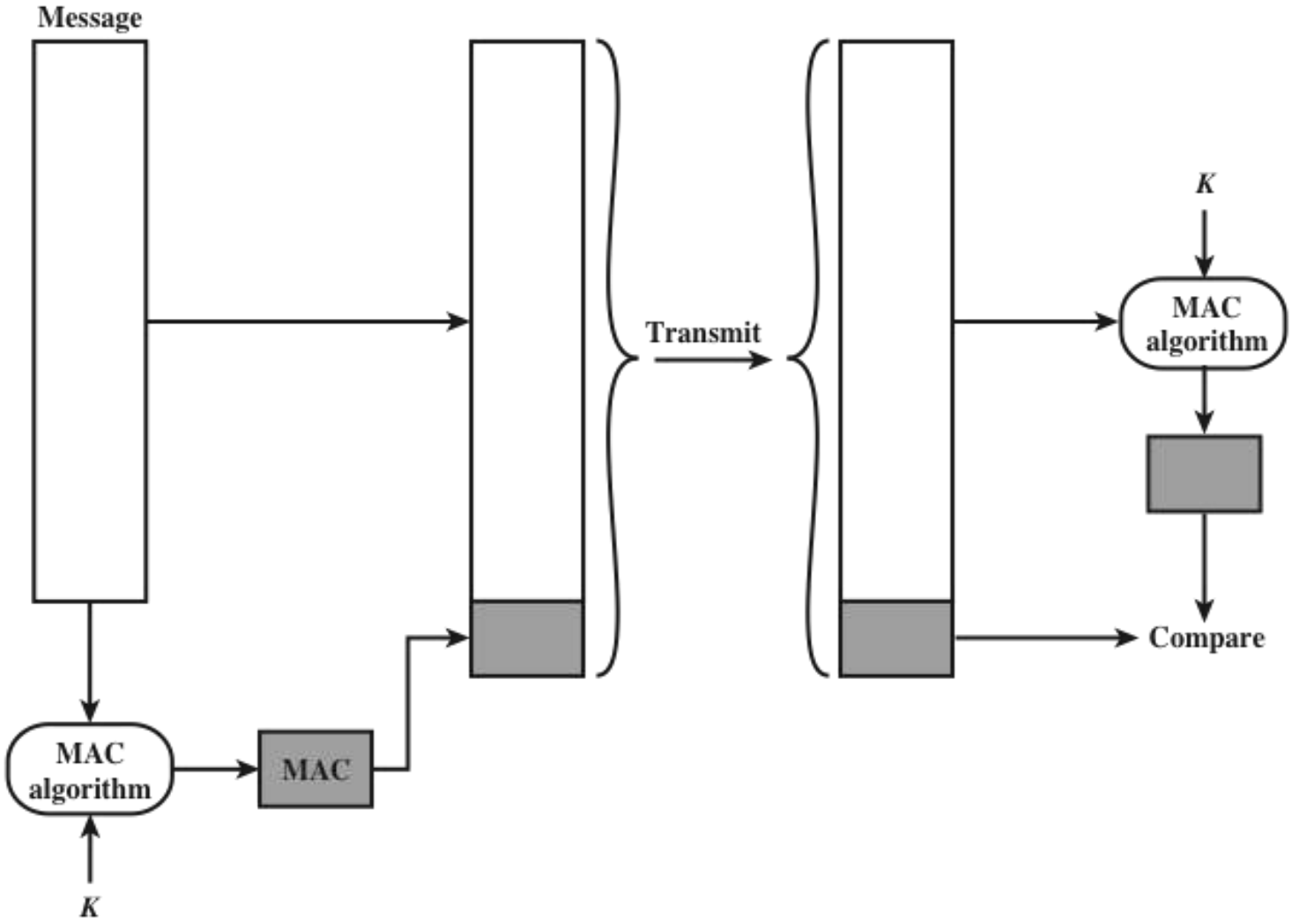
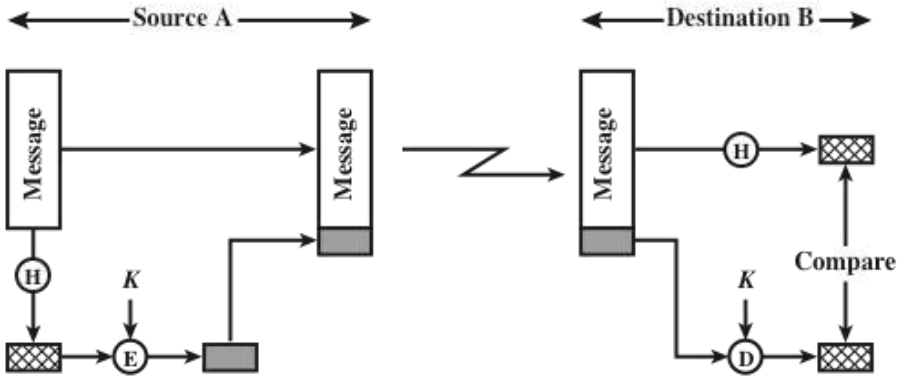


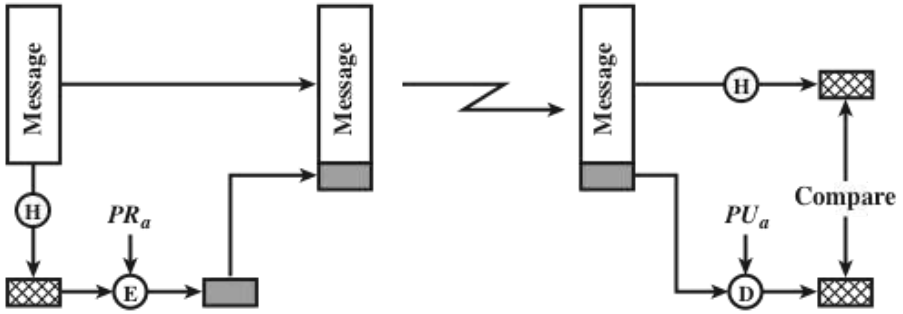
Figure 3.1 Message Authentication Using a Message Authentication Code (MAC)

ONE-WAY HASH FUNCTIONS

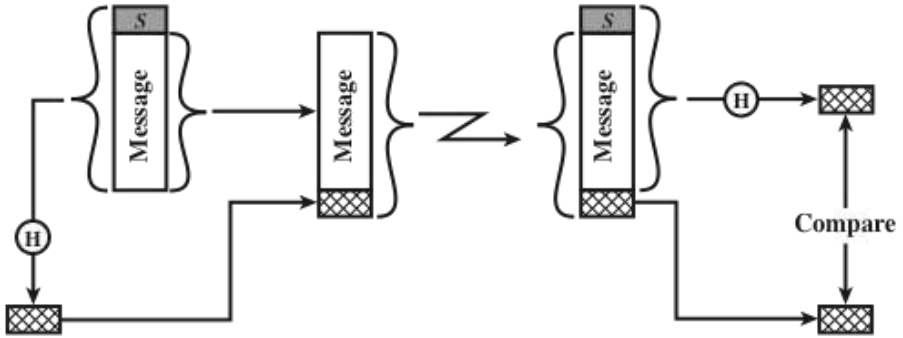
- Accepts a variable-size message *M* as input and produces a fixed-size message digest H(*M*) as output
- Does not take a secret key as input
- To authenticate a message, the message digest is sent with the message in such a way that the message digest is authentic



(a) Using conventional encryption



(b) Using public-key encryption



(c) Using secret value

Figure 3.2 Message Authentication Using a One-Way Hash Function

SECURE HASH FUNCTIONS

- Is important not only in message authentication but in digital signatures
- Purpose is to produce a "fingerprint" of a file, message, or other block of data
- To be useful for message authentication, a hash function H must have the following properties:

1. H can be applied to a block of data of any size.
2. H produces a fixed-length output.
3. H(x) is relatively easy to compute for any given x, making both hardware and software implementations practical.
4. For any given code h, it is computationally infeasible to find x such that H(x) = h. A hash function with this property is referred to as one-way or preimage resistant.
5. For any given block x, it is computationally infeasible to find y x with H(y) = H(x). A hash function with this property is referred to as second preimage resistant. This is sometimes referred to as weak collision resistant.
6. It is computationally infeasible to find any pair (x, y) such that H(x) = H(y).
   - A hash function with this property is referred to as collision resistant. This is sometimes referred to as strong collision resistant.

SECURITY OF HASH FUNCTIONS

- There are two approaches to attacking a secure hash function:
  - Cryptanalysis
    - Involves exploiting logical weaknesses in the algorithm
  - Brute-force attack
    - The strength of a hash function against this attack depends solely on the length of the hash code produced by the algorithm

	bit 1	bit 2	• • •	bit n
block 1	b_{11}	b_{21}		b_{n1}
block 2	b_{12}	b_{22}		b_{n2}
	•	•	•	•
	•	•	•	•
	•	•	•	•
block m	b_{1m}	b_{2m}		b_{nm}
hash code	C_1	C_2		C_n

Figure 3.3 Simple Hash Function Using Bitwise XOR

The SHA Secure Hash Function

- SHA was developed by NIST and published as a federal information processing standard (FIPS 180) in 1993
- Was revised in 1995 as SHA-1 and published as FIPS 180-1
  - The actual standards document is entitled "Secure Hash Standard"
- Based on the hash function MD4 and its design closely models MD4
- Produces 160-bit hash values
- In 2005 NIST announced the intention to phase out approval of SHA-1 and move to a reliance on SHA-2 by 2010

TABLE 3.1
COMPARISON OF SHA PARAMETERS

	SHA-1	SHA-224	SHA-256	SHA-384	SHA-512
Message Digest Size	160	224	256	384	512
Message Size	$< 2^{64}$	$< 2^{64}$	$< 2^{64}$	$< 2^{128}$	$< 2^{128}$
Block Size	512	512	512	1024	1024
Word Size	32	32	32	64	64
Number of Steps	80	64	64	80	80

Note: All sizes are measured in bits.

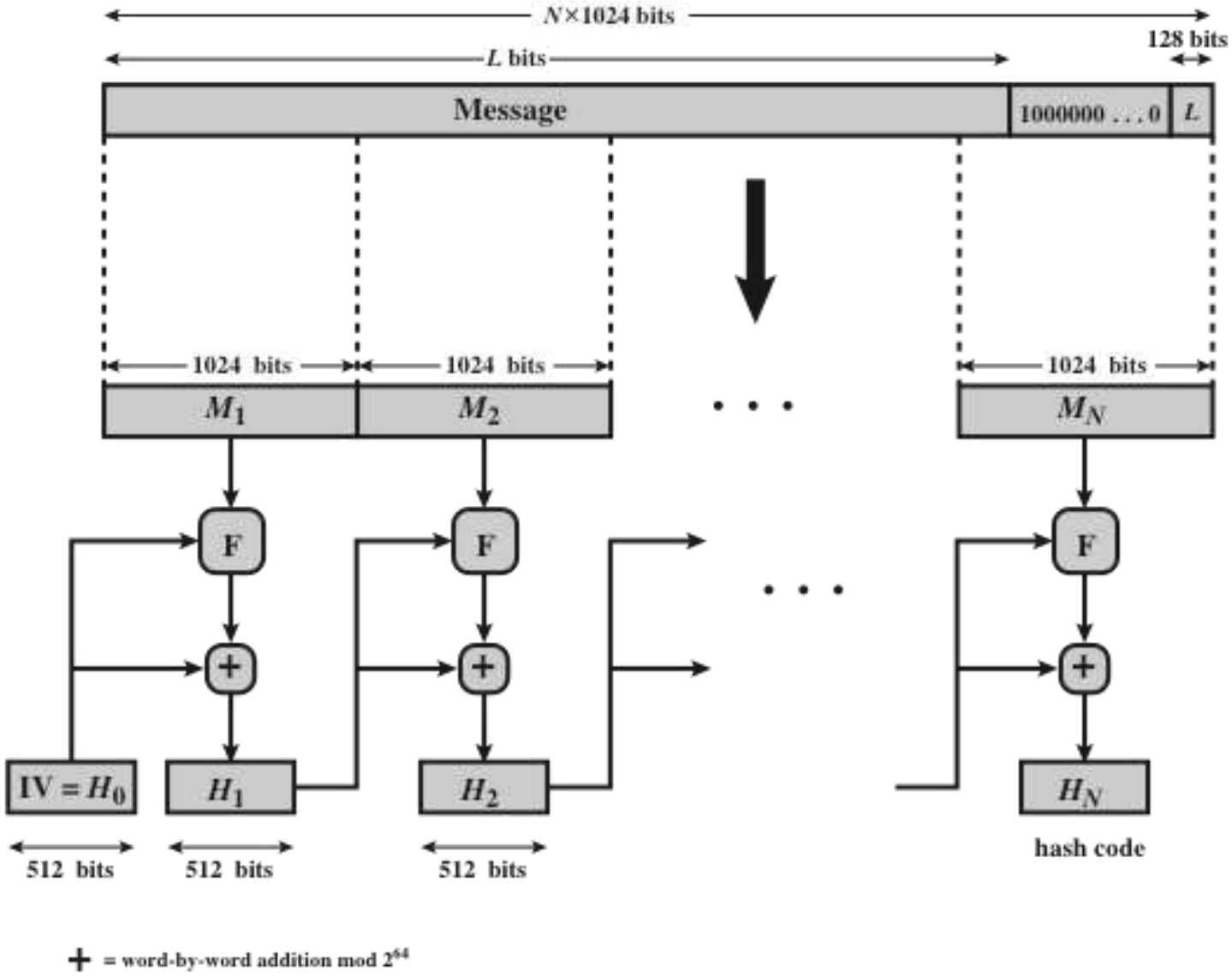


Figure 3.4 Message Digest Generation Using SHA-512

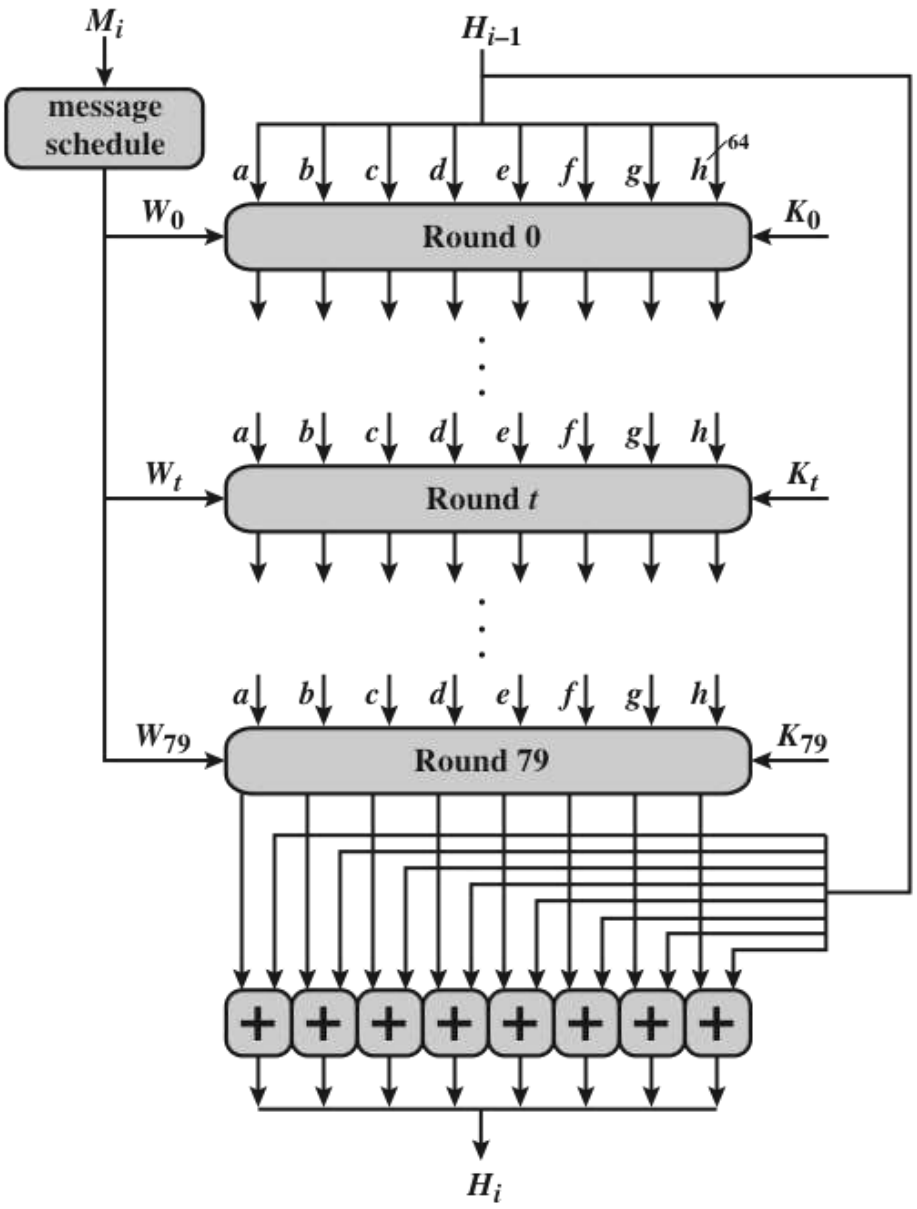


Figure 3.5 SHA-512 Processing of a Single 1024-Bit Block

SHA-3

1. It must be possible to replace SHA-2 with SHA-3 in any application by a simple drop-in substitution. Therefore, SHA-3 must support hash value lengths of 224, 256, 384, and 512 bits.

2. SHA-3 must preserve the online nature of SHA-2. That is, the algorithm must process comparatively small blocks (512 or 1024 bits) at a time instead of requiring that the entire message be buffered in memory before processing it.

Basic requirements that must be satisfied by any candidate for SHA-3

HMAC

- There has been an increased interest in developing a MAC derived from a cryptographic hash code, such as SHA-1
  - Cryptographic hash functions generally execute faster in software than conventional encryption algorithms such as DES
  - Library code for cryptographic hash functions is widely available
  - A hash function such as SHA-1 was not designed for use as a MAC and cannot be used directly for that purpose because it does not rely on a secret key
- There have been a number of proposals for the incorporation of a secret key into an existing hash algorithm
  - The approach that has received the most support is HMAC

HMAC

- Has been issued as RFC 2104
- Has been chosen as the mandatory-to-implement MAC for IP Security
- Is used in other Internet protocols, such as Transport Layer Security (TLS) and Secure Electronic Transaction (SET)

HMAC Design Objectives

- To use, without modifications, available hash functions --- in particular, hash functions that perform well in software, and for which code is freely and widely available
- To allow for easy replaceability of the embedded hash function in case faster or more secure hash functions are found or required
- To preserve the original performance of the hash function without incurring a significant degradation
- To use and handle keys in a simple way
- To have a well understood cryptographic analysis of the strength of the authentication mechanism based on reasonable assumptions on the embedded hash function

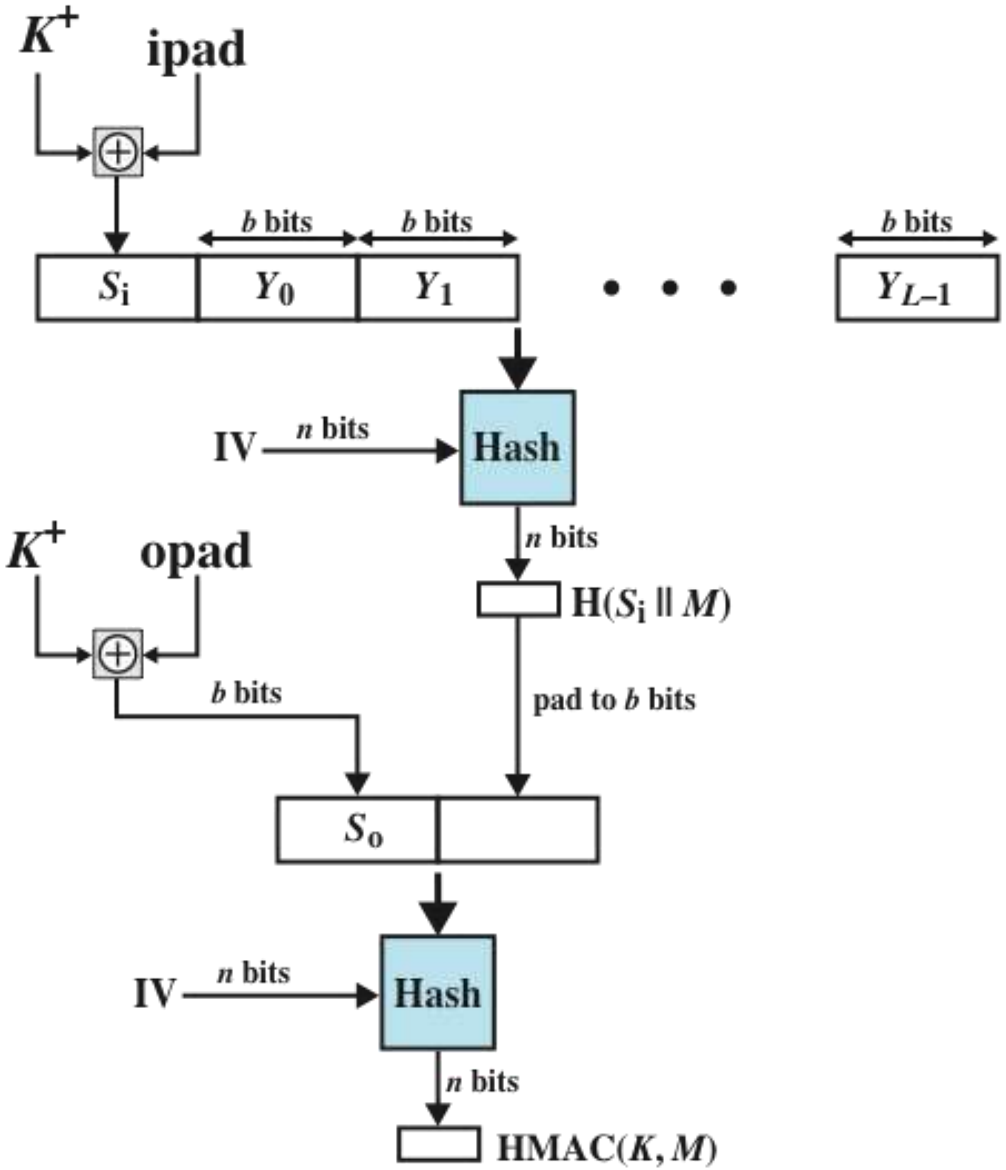
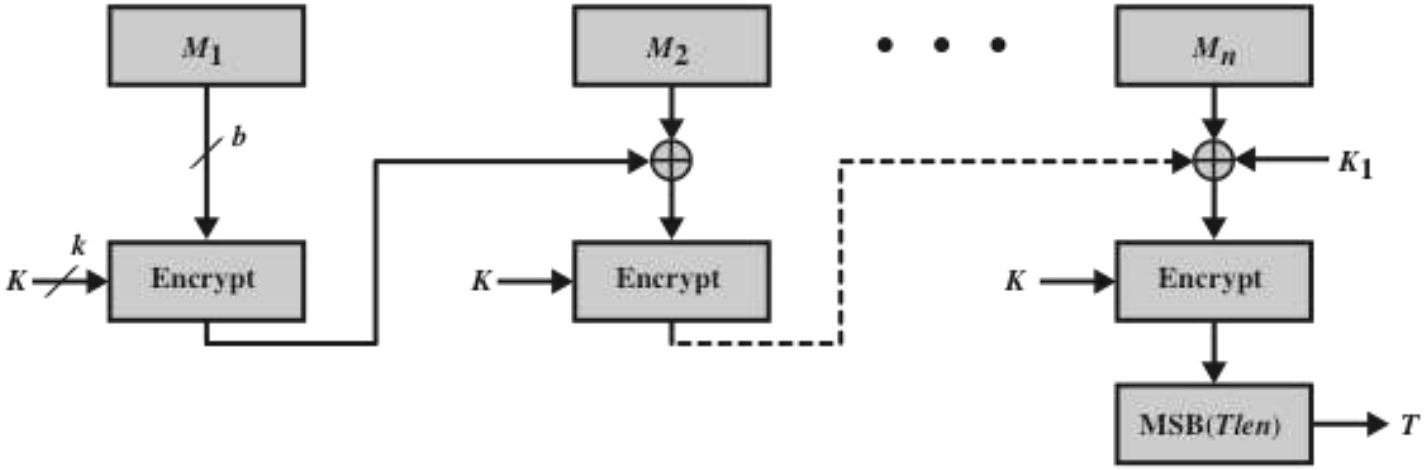
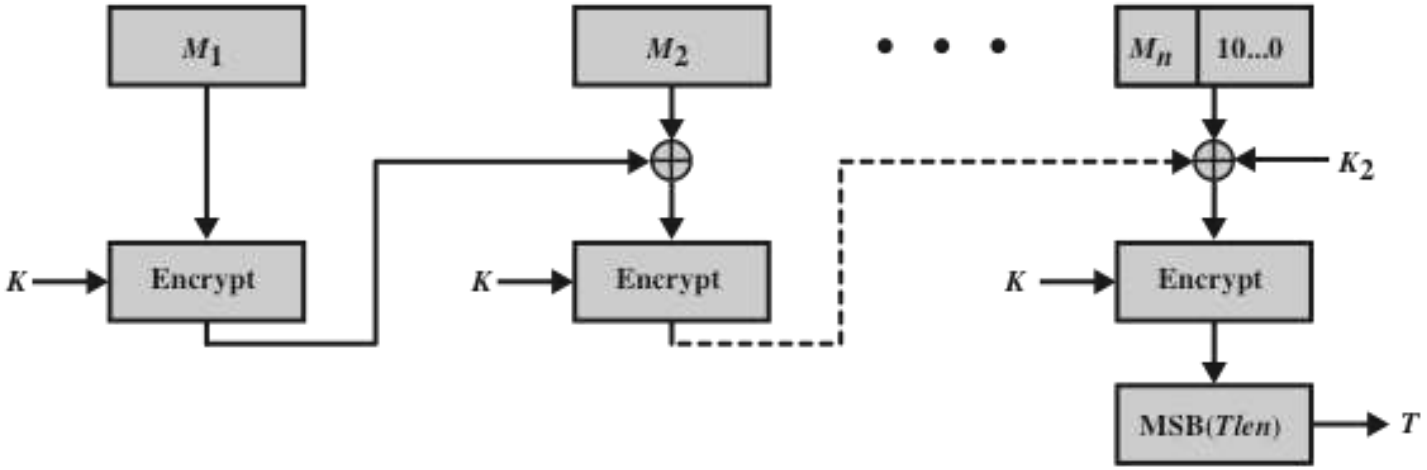


Figure 3.6 HMAC Structure



(a) Message length is integer multiple of block size

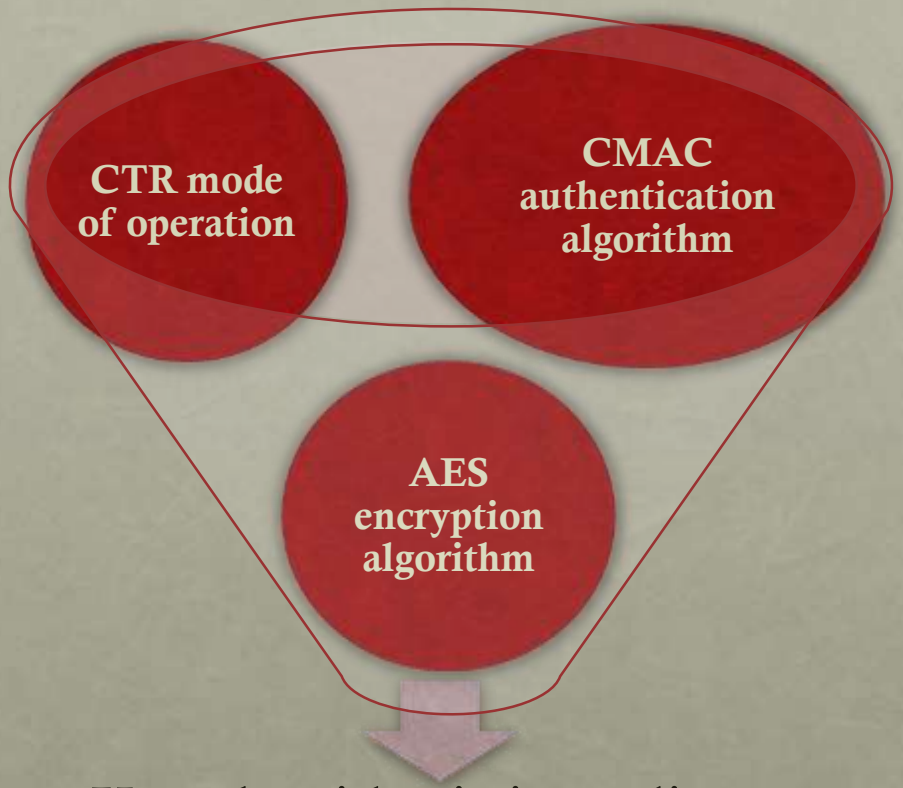


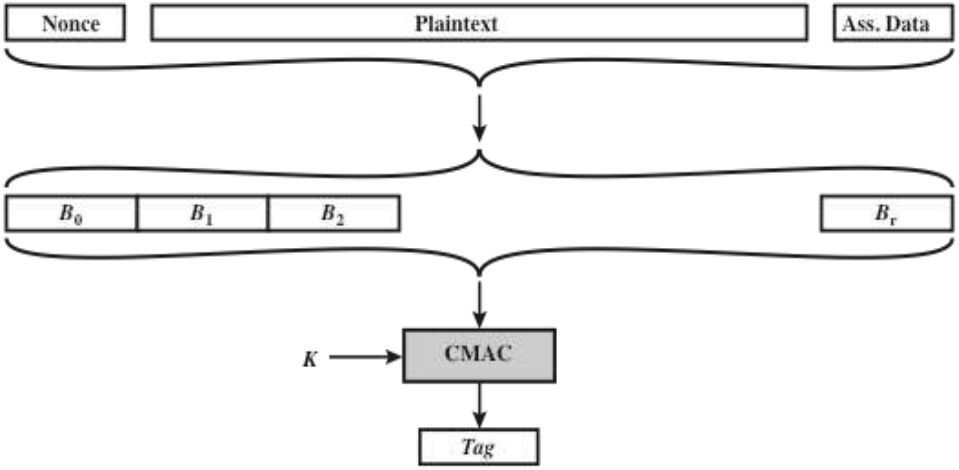
(b) Message length is not integer multiple of block size

Figure 3.7 Cipher-Based Message Authentication Code (CMAC)

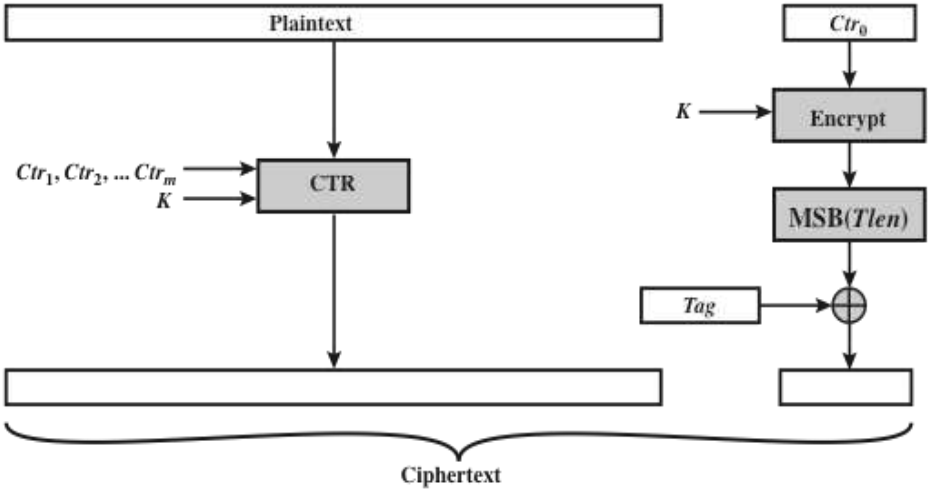
COUNTER WITH CIPHER BLOCK CHAINING-MESSAGE AUTHENTICATION CODE (CCM)

- NIST standard SP 800-38C
- Referred to as an *authenticated encryption* mode
  - "Authenticated encryption" is a term used to describe encryption systems that simultaneously protect confidentiality and authenticity of communications
- A single key is used for both encryption and MAC algorithms





(a) Authentication



(b) Encryption

Figure 3.8 Counter with Cipher Block Chaining-Message Authentication Code (CCM)

PUBLIC-KEY ENCRYPTION STRUCTURE

- First publicly proposed by Diffie and Hellman in 1976
- Based on mathematical functions rather than on simple operations on bit patterns
- Is asymmetric, involving the use of two separate keys

Misconceptions:

- Public-key encryption is more secure from cryptanalysis than conventional encryption
- Public-key encryption is a general-purpose technique that has made conventional encryption obsolete
- There is a feeling that key distribution is trivial when using public-key encryption, compared to the rather cumbersome handshaking involved with key distribution centers for conventional encryption

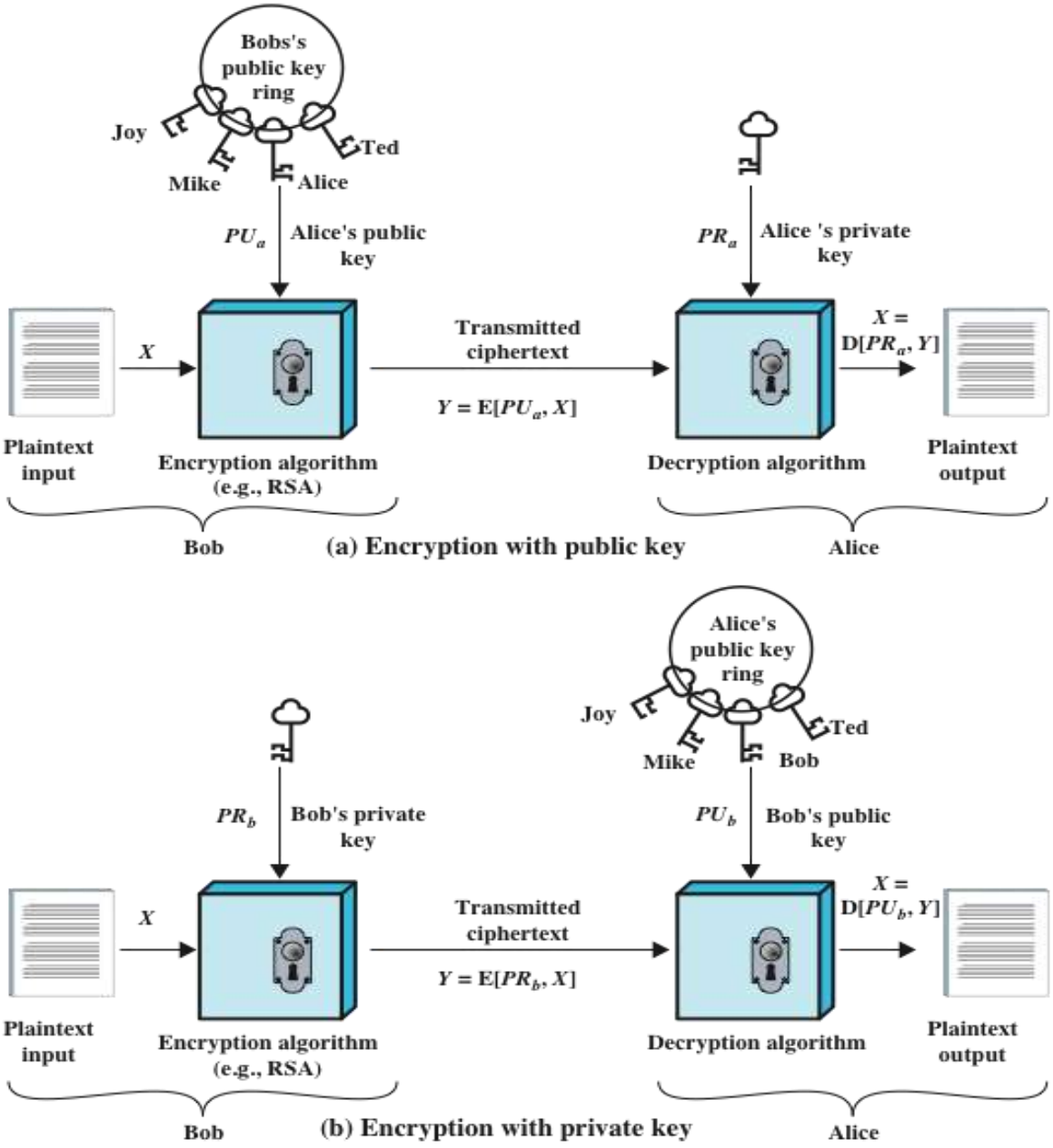


Figure 3.9 Public-Key Cryptography

APPLICATIONS FOR PUBLIC-KEY CRYPTOSYSTEMS

- Public-key systems are characterized by the use of a cryptographic type of algorithm with two keys, one held private and one available publicly
- Depending on the application, the sender uses either the sender's private key, the receiver's public key, or both to perform some type of cryptographic function

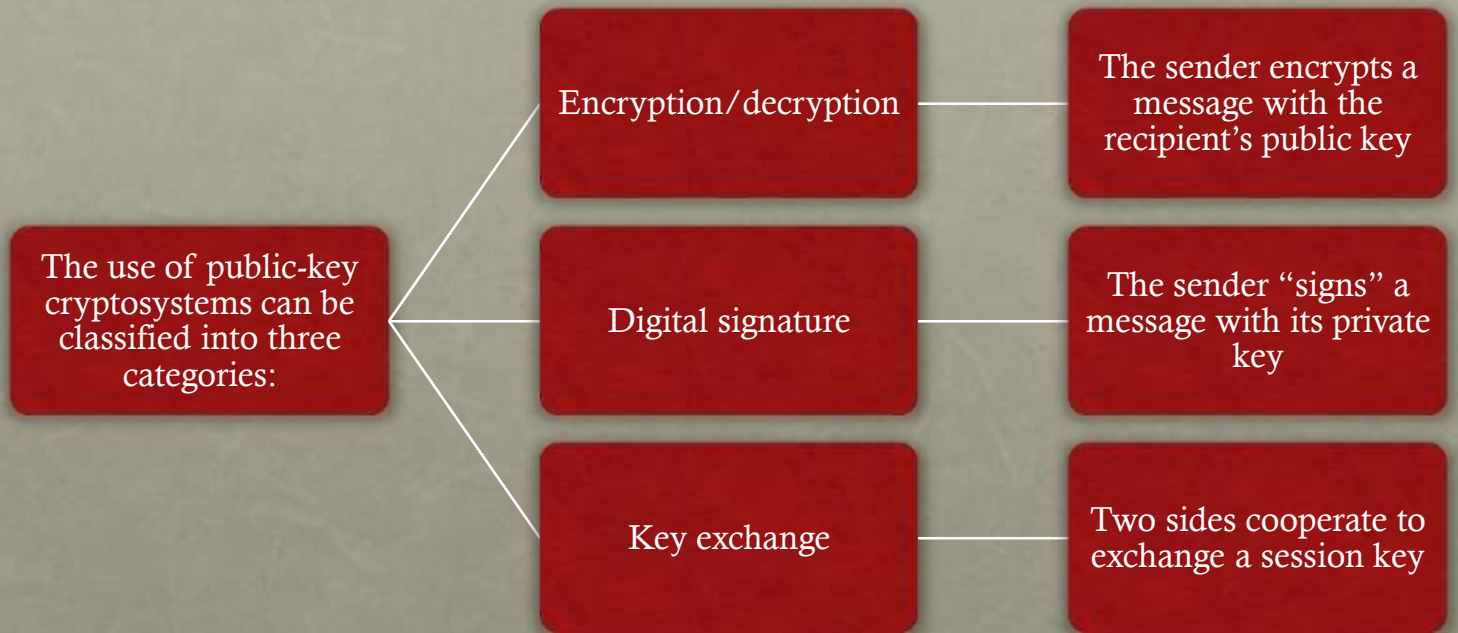


TABLE 3.2
APPLICATIONS FOR PUBLIC-KEY CRYPTOSYSTEMS

Algorithm	Encryption/Decryption	Digital Signature	Key Exchange
RSA	Yes	Yes	Yes
Diffie-Hellman	No	No	Yes
DSS	No	Yes	No
Elliptic Curve	Yes	Yes	Yes

RSA

- By Rivest, Shamir & Adleman of MIT in 1977
- Best known & widely used public-key scheme
- Based on exponentiation in a finite (Galois) field over integers modulo a prime
  - nb. modular exponentiation takes $O((\log n)^3)$ operations (easy)
- Uses large integers (eg. 1024 bits)
- Security due to cost of factoring large numbers
  - nb. factorization takes $O(e^{\log n \log \log n})$ operations (hard)

Key Generation	
Select p, q	p and q both prime, $p \neq q$
Calculate $n = p \times q$	
Calculate $\phi(n) = (p - 1)(q - 1)$	
Select integer e	$\gcd(\phi(n), e) = 1;\ 1 < e < \phi(n)$
Calculate d	$de \bmod \phi(n) = 1$
Public key	$KU = \{e, n\}$
Private key	$KR = \{d, n\}$

Encryption	
Plaintext:	$M < n$
Ciphertext:	$C = M^e \pmod{n}$

Decryption	
Ciphertext:	C
Plaintext:	$M = C^d \pmod{n}$

Figure 3.10 The RSA Algorithm

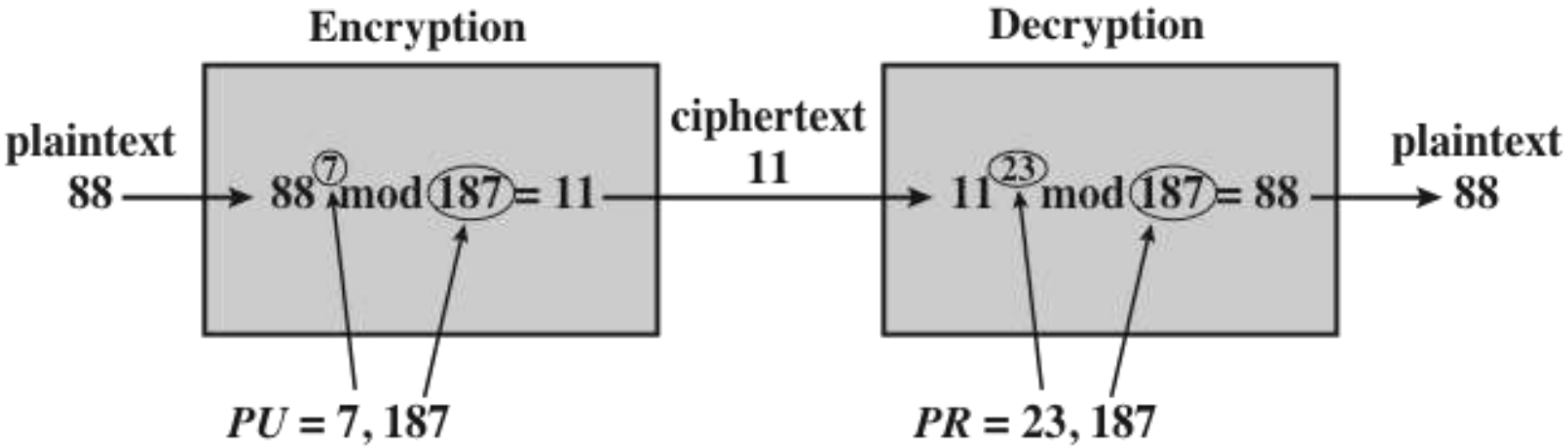


Figure 3.11 Example of RSA Algorithm

WHY RSA WORKS

- Because of Euler's Theorem:
  - $a^{\phi(n)} \bmod n = 1$ where $\gcd(a,n)=1$
- In RSA have:
  - $n=p.q$
  - $\phi(n)=(p-1)(q-1)$
  - Carefully chose e & d to be inverses $\bmod \phi(n)$
  - Hence $e.d=1+k.\phi(n)$ for some k
- Hence :

$$C^d = M^{e.d} = M^{1+k.\phi(n)} = M^1.(M^{\phi(n)})^k$$

$$= M^1.(1)^k = M^1 = M \bmod n$$

DIFFIE-HELLMAN KEY EXCHANGE

- First published public-key algorithm
- A number of commercial products employ this key exchange technique
- Purpose of the algorithm is to enable two users to exchange a secret key securely that then can be used for subsequent encryption of messages
  - The algorithm itself is limited to the exchange of the keys
- Depends for its effectiveness on the difficulty of computing discrete logarithms

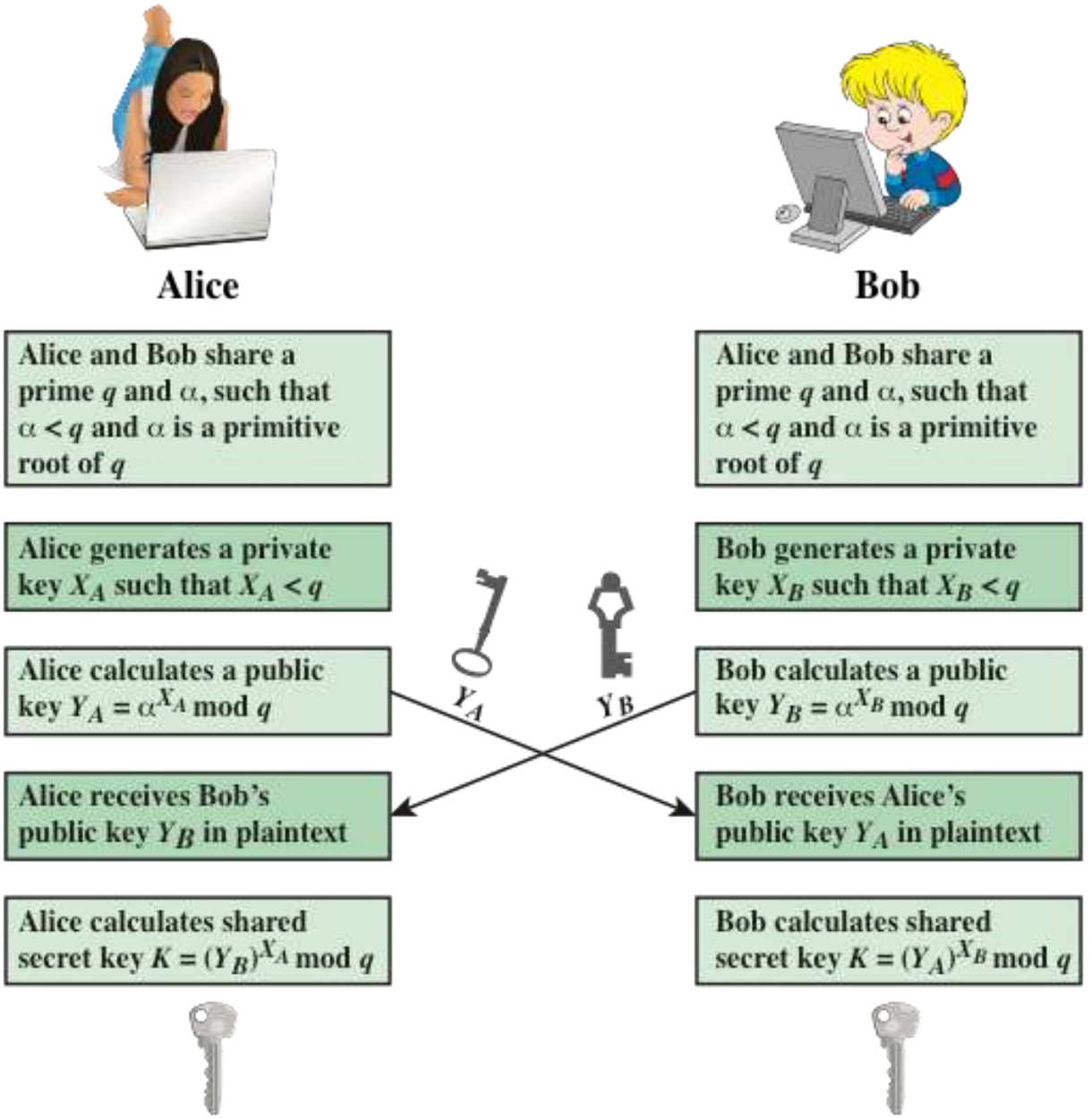


Figure 3.12 Diffie-Hellman Key Exchange

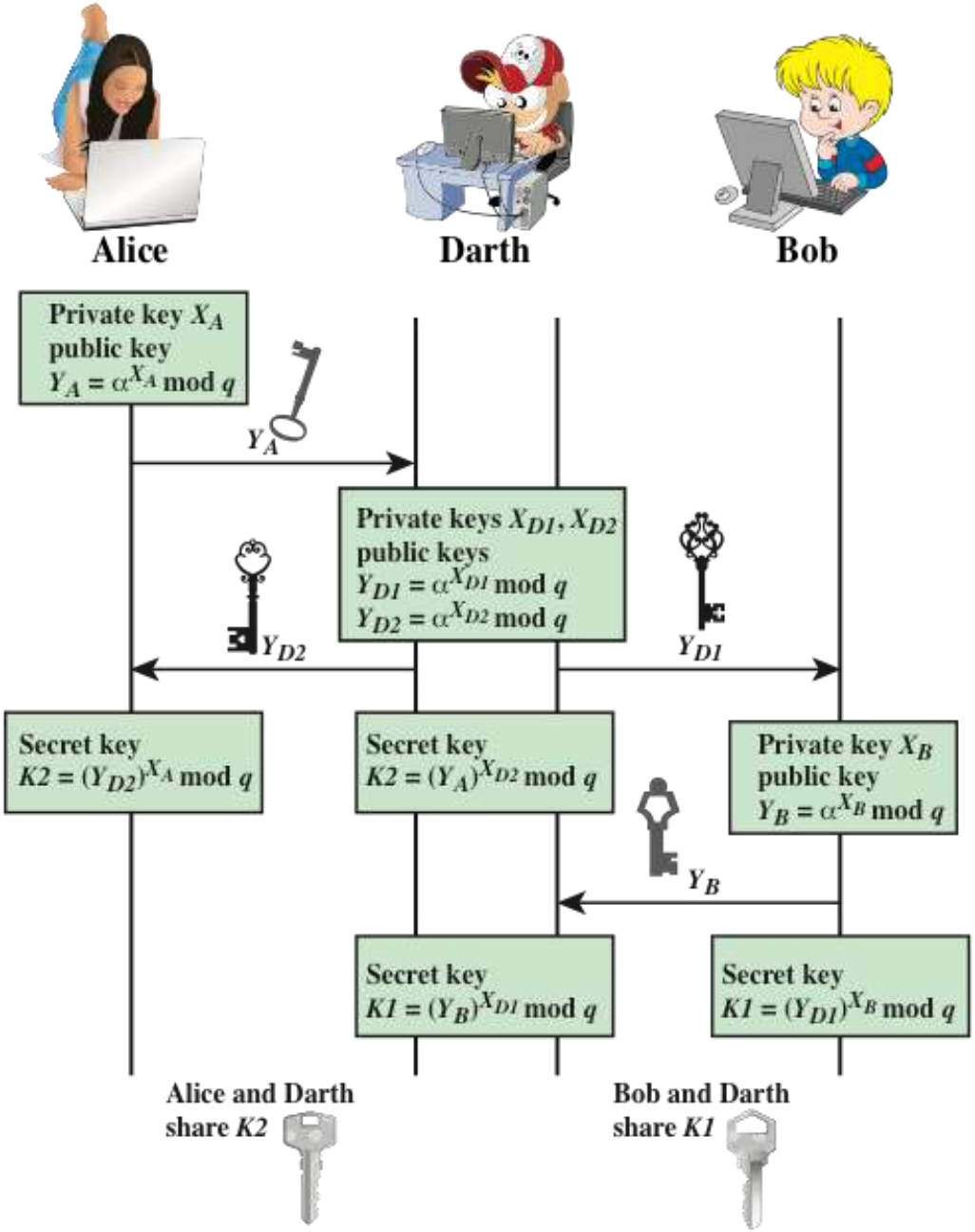


Figure 3.13 Man-in-the-Middle Attack

DIFFIE-HELLMAN EXAMPLE

- Users Alice & Bob who wish to swap keys:
- Agree on prime $q=353$ and $a=3$
- Select random secret keys:
  - A chooses $x_A=97$, B chooses $x_B=233$
- Compute respective public keys:
  - $y_A = 3^{97} \mod 353 = 40$ (Alice)
  - $y_B = 3^{233} \mod 353 = 248$ (Bob)
- Compute shared session key as:
  - $K_{AB} = y_B^{x_A} \mod 353 = 248^{97} = 160$ (Alice)
  - $K_{AB} = y_A^{x_B} \mod 353 = 40^{233} = 160$ (Bob)

DISCRETE LOGARITHM

- Ordinary logarithm:
  - $a^x = b$
  - $x = log_a(b)$
- Discrete logarithm:
  - $b = a^i \bmod p \ (0 \leq i \leq p-1)$
    - a: primitive root of prime number p
    - Can generate all integers from 1 to $p-1$
    - i.e. $a^1 \bmod p$, $a^2 \bmod p$, $a^{p-1} \bmod p$ are distinct
  - $i = dlog_{a,p}(b)$

DIGITAL SIGNATURE STANDARD (DSS)

- FIPS PUB 186
- Makes use of the SHA-1 and presents a new digital signature technique, the Digital Signature Algorithm (DSA)
- Originally proposed in 1991 and revised in 1993 and again in 1996
- Uses an algorithm that is designed to provide only the digital signature function
- Unlike RSA, it cannot be used for encryption or key exchange

ELLIPTIC-CURVE CRYPTOLOGY (ECC)

- Technique is based on the use of a mathematical construct known as the elliptic curve
- Principal attraction of ECC compared to RSA is that it appears to offer equal security for a far smaller bit size, thereby reducing processing overhead
- The confidence level in ECC is not yet as high as that in RSA

SUMMARY

- Approaches to message authentication
  - Authentication using conventional encryption
  - Message authentication without message encryption
- Secure hash functions
  - Hash function requirements
  - Security of hash functions
  - Simple hash functions
  - The SHA secure hash function SHA-3
- Digital signatures
- Message authentication codes
  - HMAC
  - MACs based on block ciphers
- Public-key cryptography principles
  - Public-key encryption structure
  - Applications for public-key cryptosystems
  - Requirements for public-key cryptography
- Public-key cryptography algorithms
  - The RSA public-key encryption algorithm
  - Diffie-Hellman key exchange
  - Other public-key cryptography algorithms