

SECURITY IN COMPUTING, FIFTH EDITION

Cryptography

Problems Addressed by Encryption

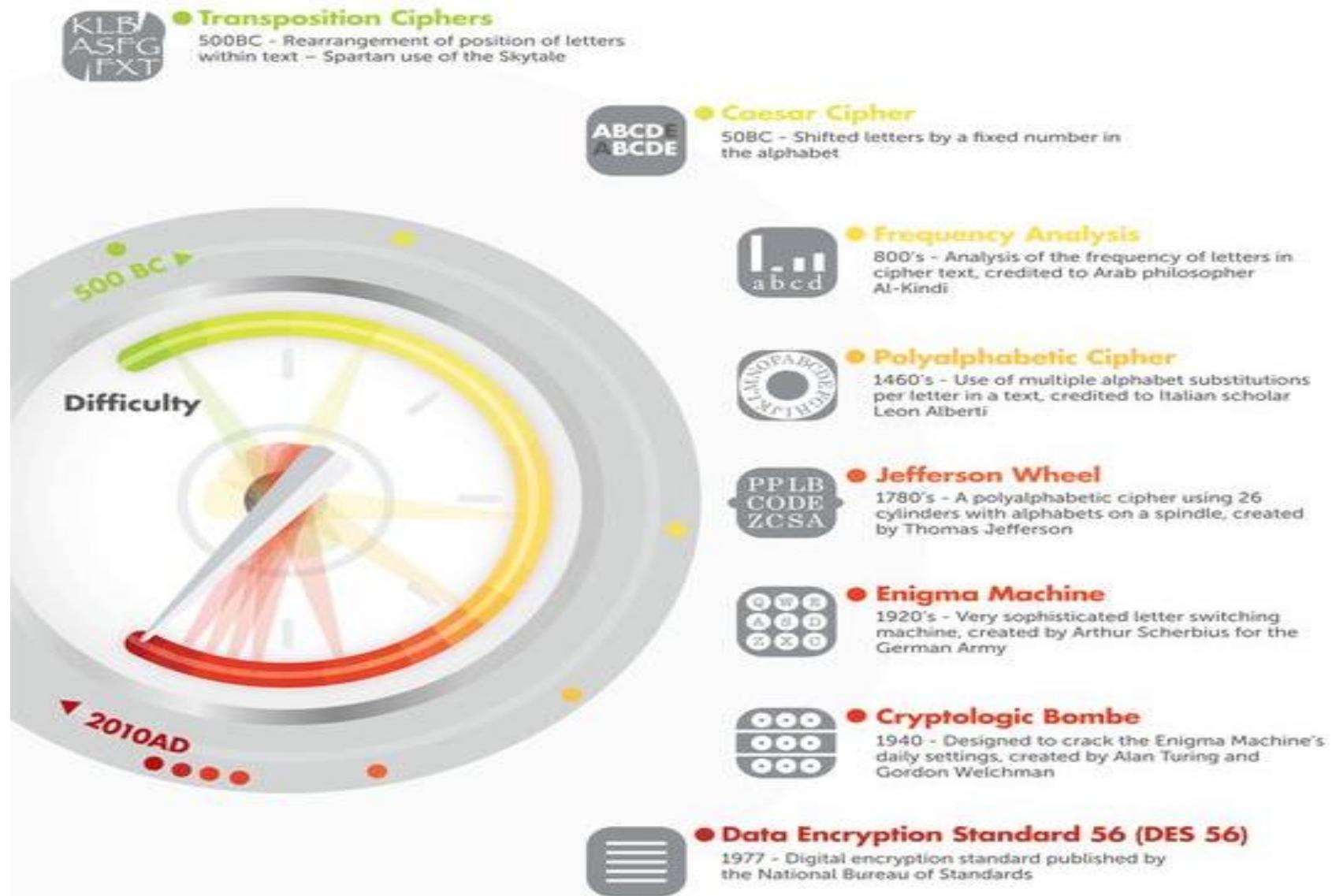
- Suppose a sender wants to send a message to a recipient. An attacker may attempt to
 - Block the message
 - Intercept the message
 - Modify the message
 - Fabricate an authentic-looking alternate message

Encryption Terminology

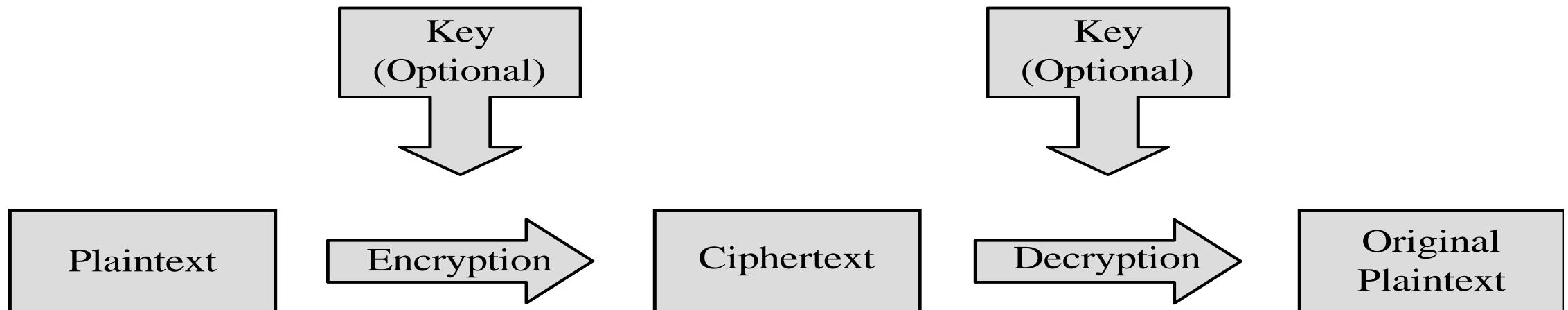
- Sender
- Recipient
- Transmission medium
- Interceptor/intruder
- Encrypt, encode, or encipher
- Decrypt, decode, or decipher
- Cryptosystem
- Plaintext
- Ciphertext

TYPES OF CRYPTOGRAPHY	
QUANTUM-BREAKABLE	QUANTUM-SECURE
 RSA encryption <p>A message is encrypted using the intended recipient's public key, which the recipient then decrypts with a private key. The difficulty of computing the private key from the public key is connected to the hardness of prime factorization.</p>	 Lattice-based cryptography <p>Security is related to the difficulty of finding the nearest point in a lattice with hundreds of spatial dimensions (where the lattice point is associated with the private key), given an arbitrary location in space (associated with the public key).</p>
 Diffie-Hellman key exchange <p>Two parties jointly establish a shared secret key over an insecure channel that they can then use for encrypted communication. The security of the secret key relies on the hardness of the discrete logarithm problem.</p>	 Code-based cryptography <p>The private key is associated with an error-correcting code and the public key with a scrambled and erroneous version of the code. Security is based on the hardness of decoding a general linear code.</p>
 Elliptic curve cryptography <p>Mathematical properties of elliptic curves are used to generate public and private keys. The difficulty of recovering the private key from the public key is related to the hardness of the elliptic-curve discrete logarithm problem.</p>	 Multivariate cryptography <p>These schemes rely on the hardness of solving systems of multivariate polynomial equations.</p>

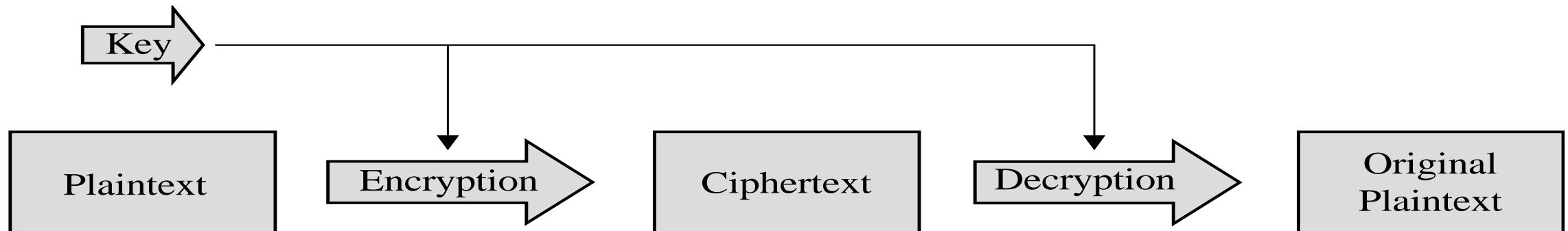
A history of encryption



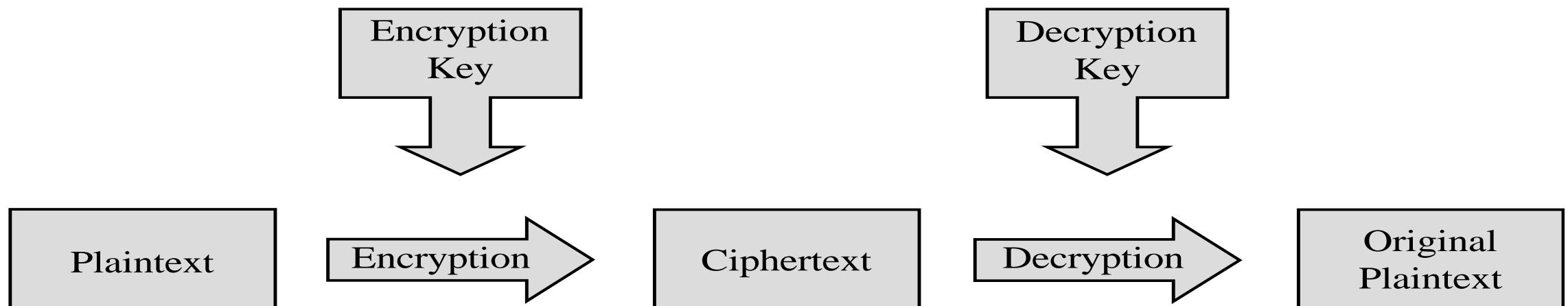
Encryption/Decryption Process



Symmetric vs. Asymmetric

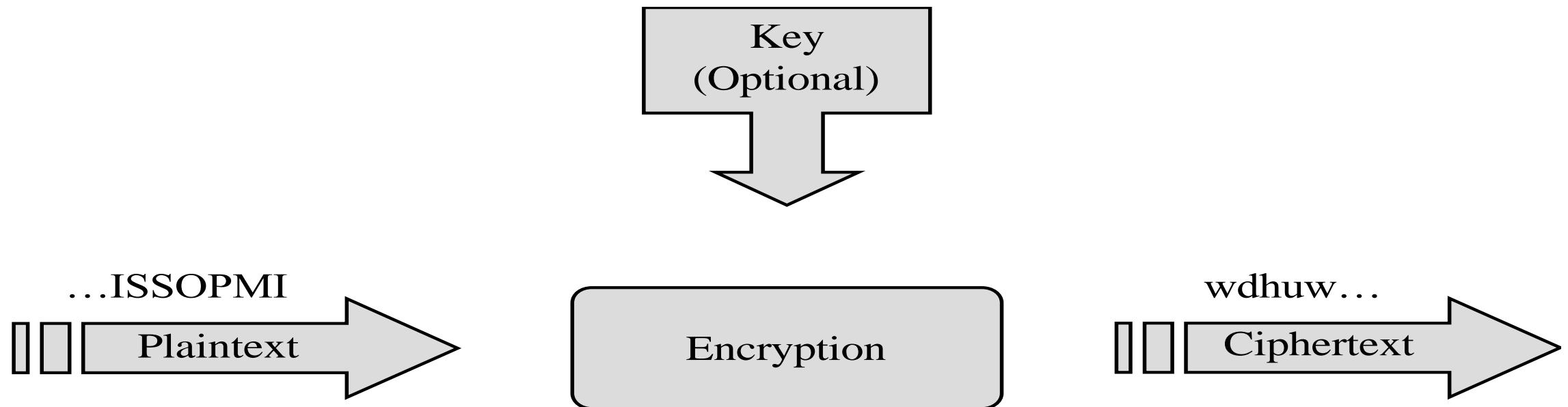


(a) Symmetric Cryptosystem

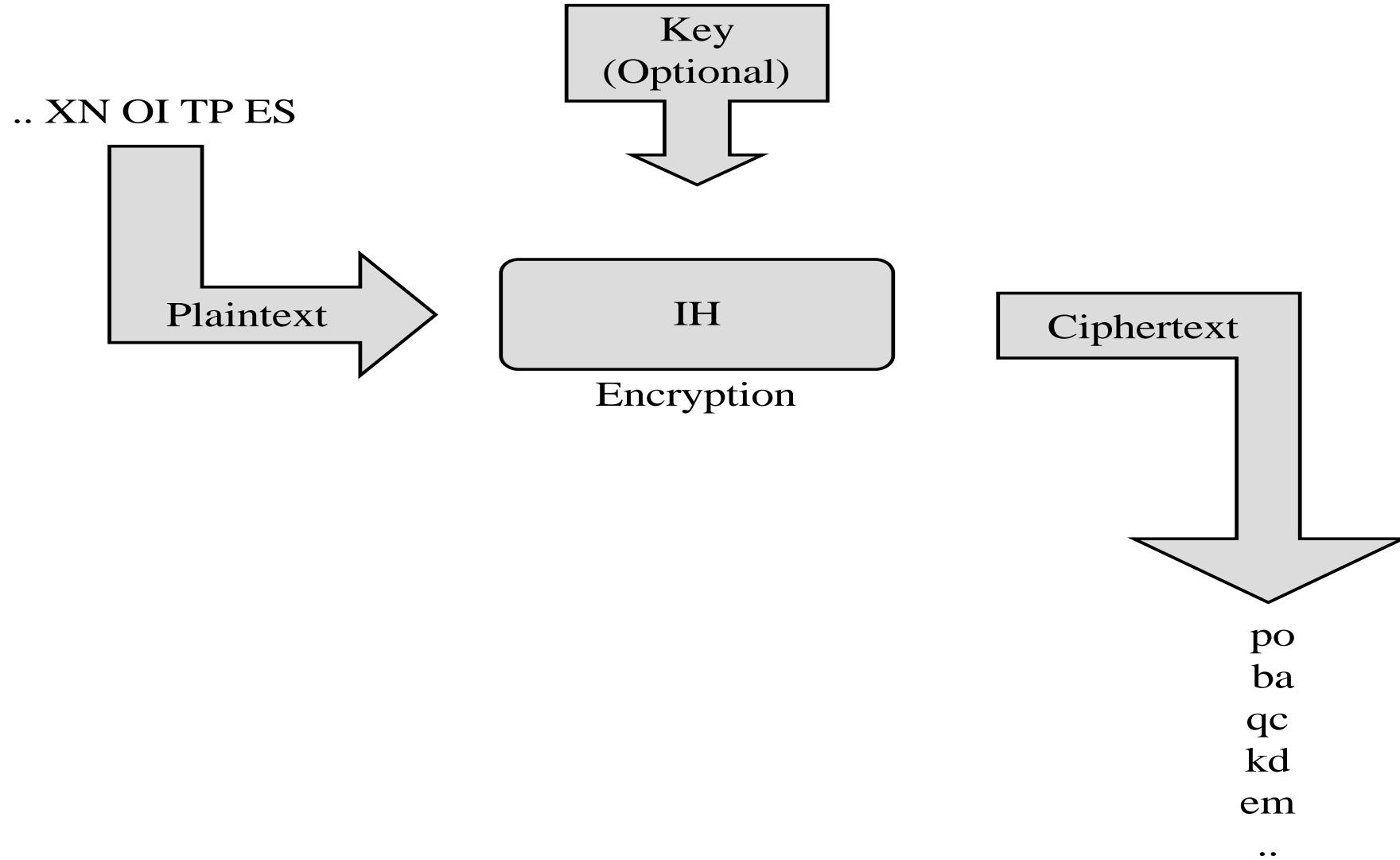


(b) Asymmetric Cryptosystem

Stream Ciphers



Block Ciphers



Diffusion

- *The idea of diffusion is to hide the relationship between the ciphertext and the plaintext.*
- *In diffusion, the statistical structure of the plaintext is dissipated into long range statistics of the ciphertext.*
- *Each plaintext digit affects the value of many ciphertext digits*

Note

Diffusion hides the relationship between the ciphertext and the plaintext.

Confusion

- *The idea of confusion is to hide the relationship between the ciphertext and the key.*
- *Confusion seeks to make the relationship between the statistics of ciphertext and the value of the encryption key as complex as possible.*

Note

Confusion hides the relationship between the ciphertext and the key.

Stream vs. Block

	Stream	Block
Advantages	<ul style="list-style-type: none">• Speed of transformation• Low error propagation	<ul style="list-style-type: none">• High diffusion• Immunity to insertion of symbol
Disadvantages	<ul style="list-style-type: none">• Low diffusion• Susceptibility to malicious insertions and modifications	<ul style="list-style-type: none">• Slowness of encryption• Padding• Error propagation

DES: The Data Encryption Standard

- Symmetric block cipher
- Developed in 1976 by IBM for the US National Institute of Standards and Technology (NIST)

Form	Operation	Properties	Strength
DES	Encrypt with one key	56-bit key	Inadequate for high-security applications by today's computing capabilities
Double DES	Encrypt with first key; then encrypt result with second key	Two 56-bit keys	Only doubles strength of 56-bit key version
Two-key triple DES	Encrypt with first key, then encrypt (or decrypt) result with second key, then encrypt result with first key (E-D-E)	Two 56-bit keys	Gives strength equivalent to about 80-bit key (about 16 million times as strong as 56-bit version)
Three-key triple DES	Encrypt with first key, then encrypt or decrypt result with second key, then encrypt result with third key (E-E-E)	Three 56-bit keys	Gives strength equivalent to about 112-bit key about 72 quintillion (72×10^{15}) times as strong as 56-bit version

DES is a block cipher, as shown in Figure.

Figure Encryption and decryption with DES



Triple DES

Figure Triple DES with two keys

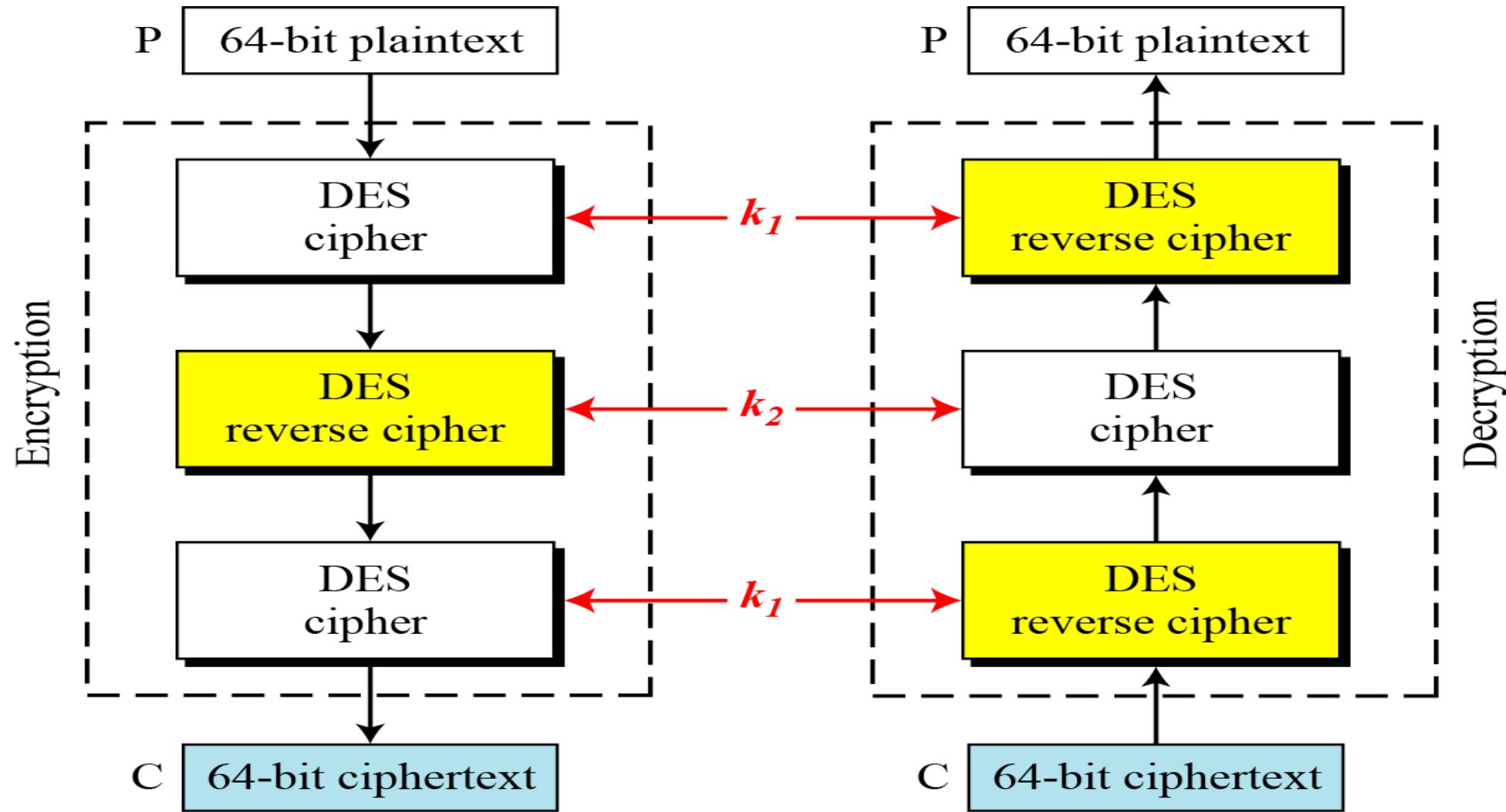
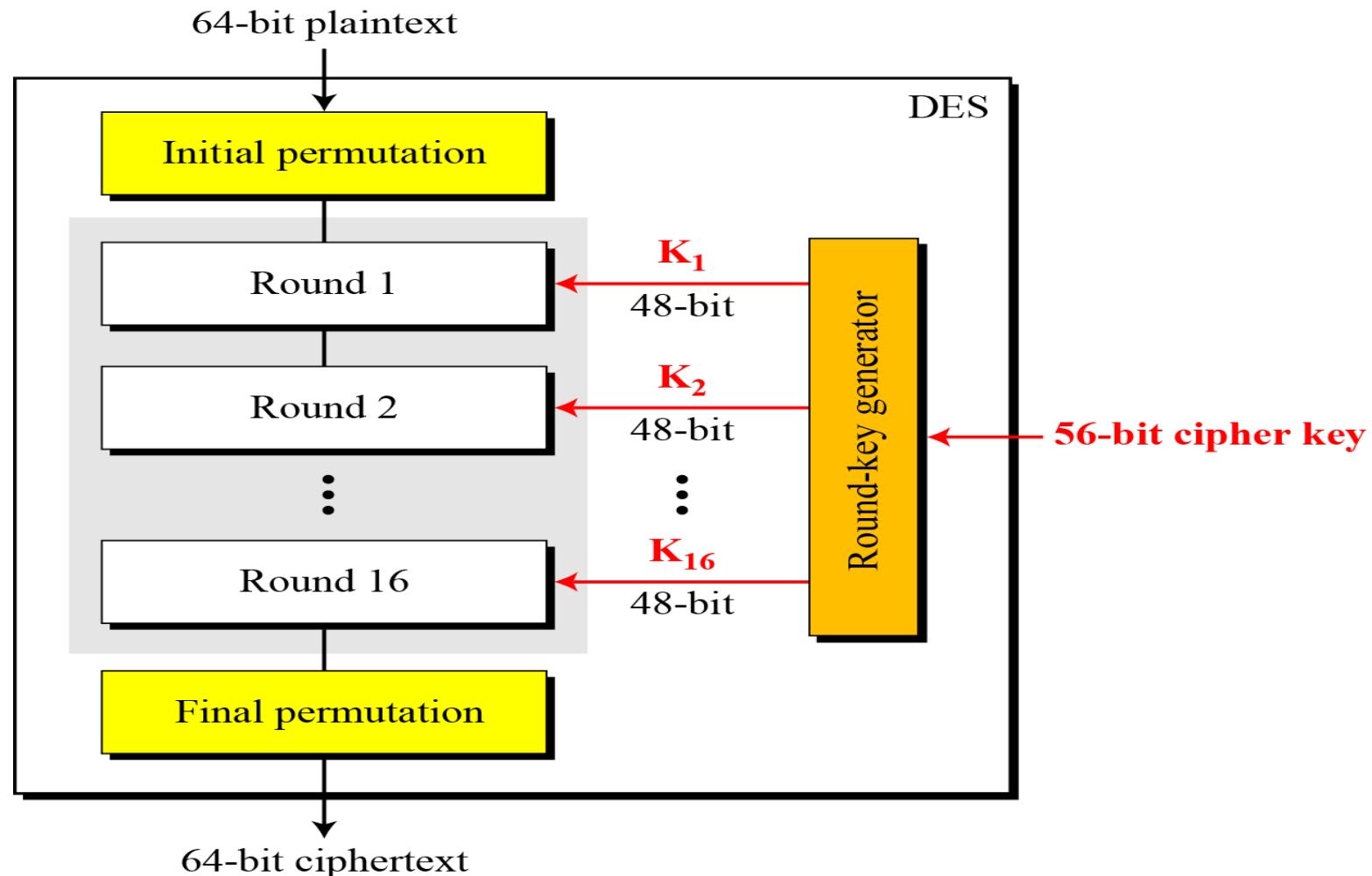
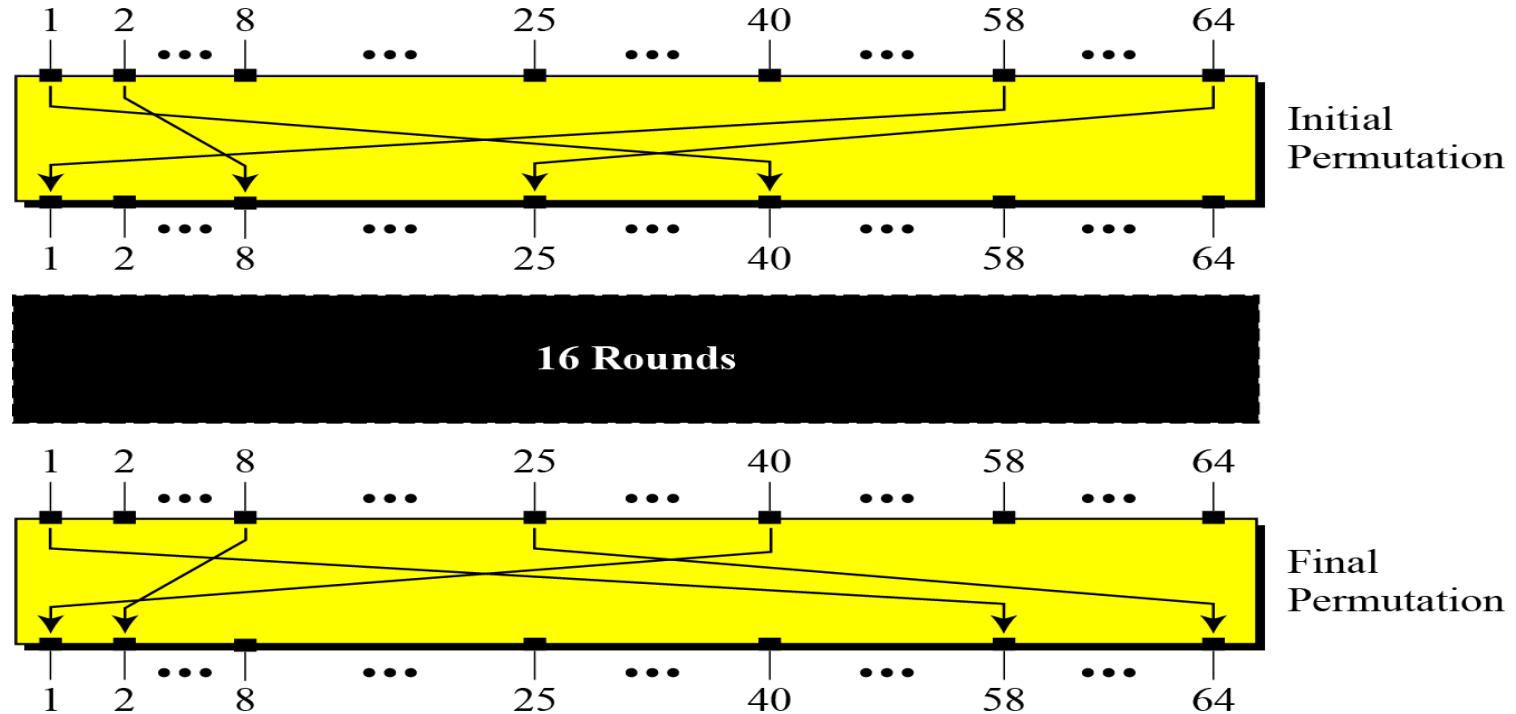


Figure General structure of DES



Initial and Final Permutations

Figure Initial and final permutation steps in DES



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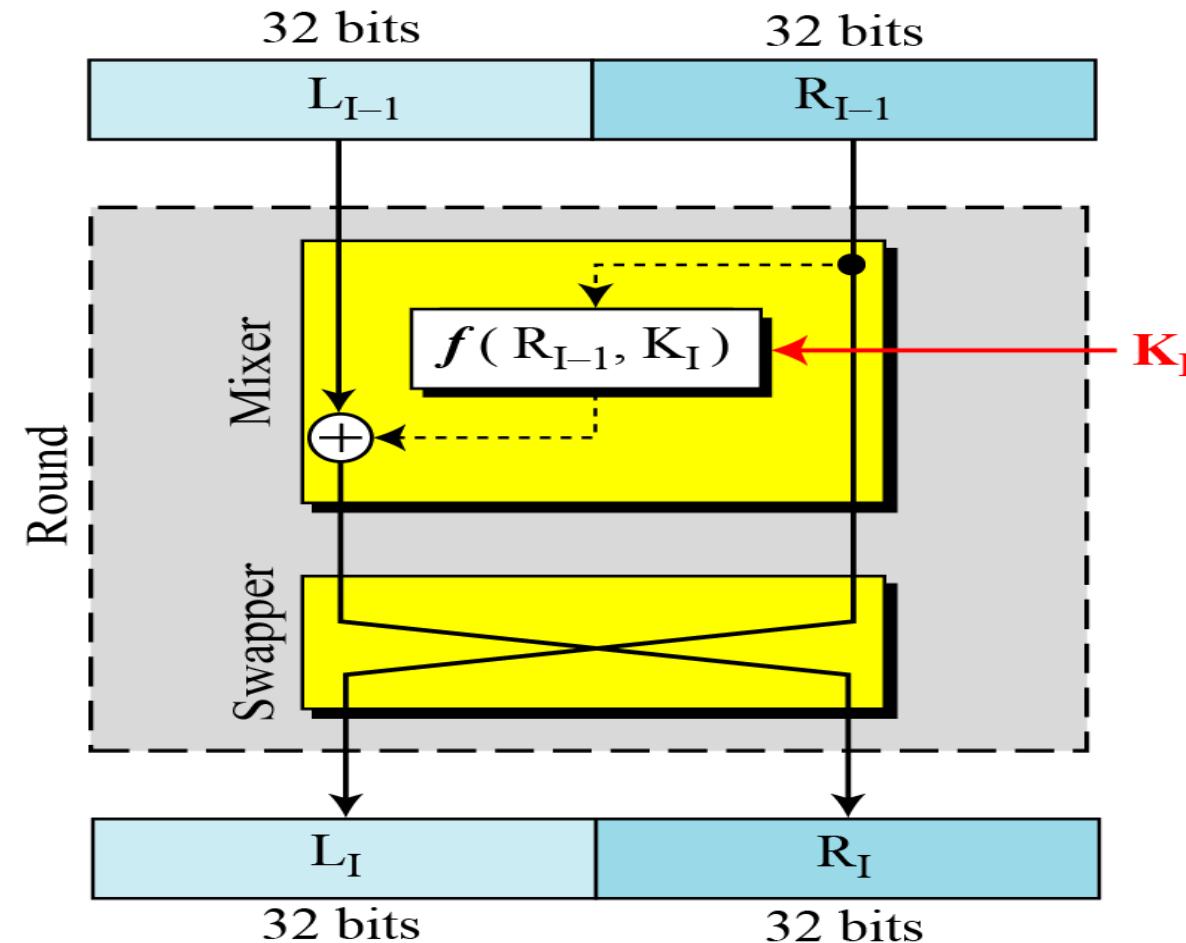
Table *Initial and final permutation tables*

<i>Initial Permutation</i>	<i>Final Permutation</i>
58 50 42 34 26 18 10 02	40 08 48 16 56 24 64 32
60 52 44 36 28 20 12 04	39 07 47 15 55 23 63 31
62 54 46 38 30 22 14 06	38 06 46 14 54 22 62 30
64 56 48 40 32 24 16 08	37 05 45 13 53 21 61 29
57 49 41 33 25 17 09 01	36 04 44 12 52 20 60 28
59 51 43 35 27 19 11 03	35 03 43 11 51 19 59 27
61 53 45 37 29 21 13 05	34 02 42 10 50 18 58 26
63 55 47 39 31 23 15 07	33 01 41 09 49 17 57 25

Rounds

DES uses 16 rounds. Each round of DES is a Feistel cipher.

Figure
*A round in DES
(encryption site)*

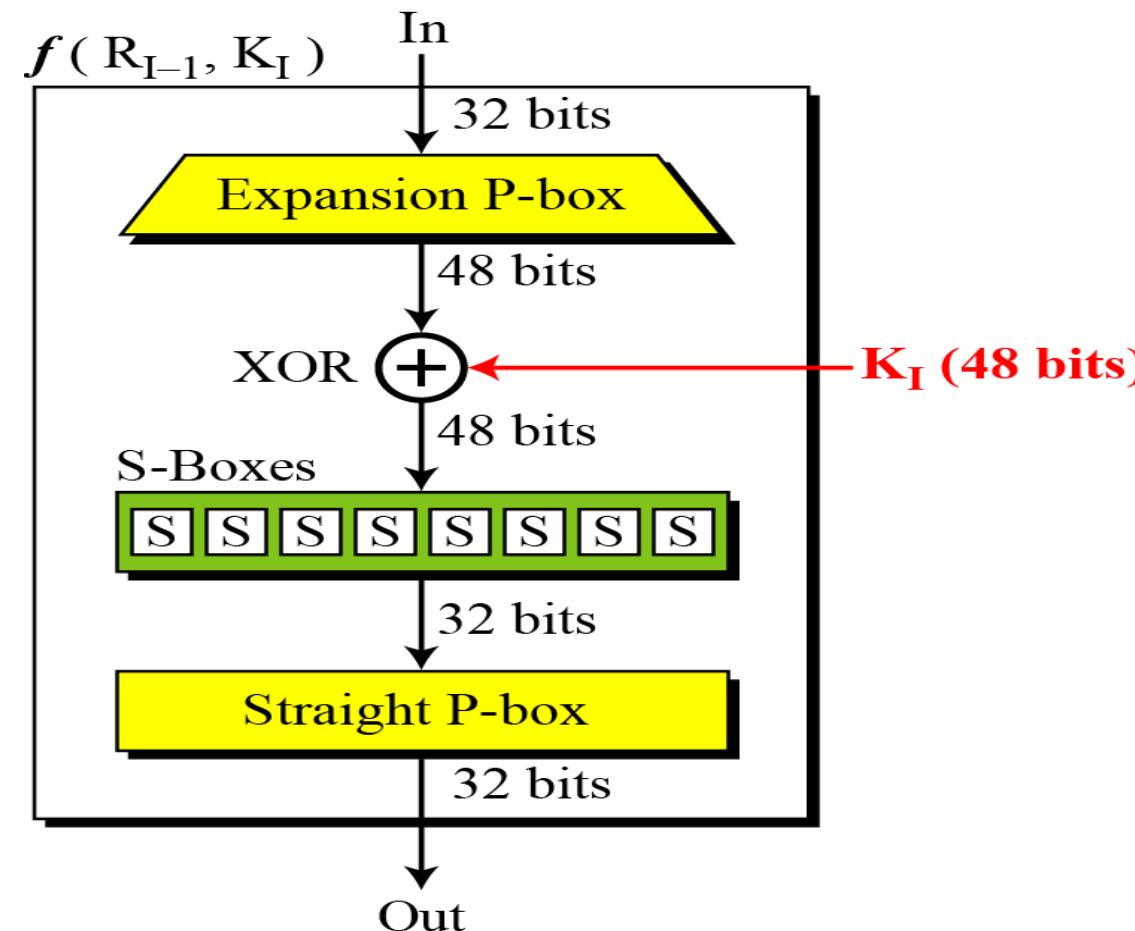


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DES Function

The heart of DES is the DES function. The DES function applies a 48-bit key to the rightmost 32 bits to produce a 32-bit output.

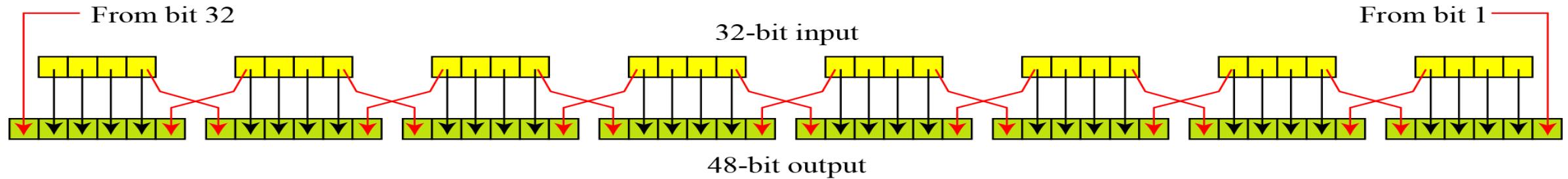
Figure
DES function



Expansion P-box

Since R_{I-1} is a 32-bit input and K_I is a 48-bit key, we first need to expand R_{I-1} to 48 bits.

Figure Expansion permutation



Continue

Although the relationship between the input and output can be defined mathematically, DES uses Table 6.2 to define this P-box.

Table Expansion P-box table

32	01	02	03	04	05
04	05	06	07	08	09
08	09	10	11	12	13
12	13	14	15	16	17
16	17	18	19	20	21
20	21	22	23	24	25
24	25	26	27	28	29
28	29	31	31	32	01

Whitener (XOR)

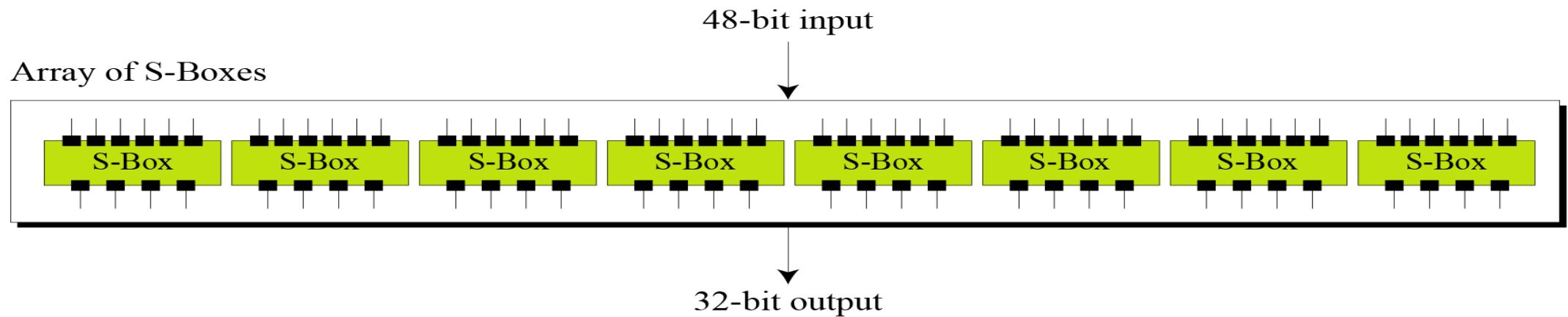
After the expansion permutation, DES uses the XOR operation on the expanded right section and the round key. Note that both the right section and the key are 48-bits in length. Also note that the round key is used only in this operation.

Continue

S-Boxes

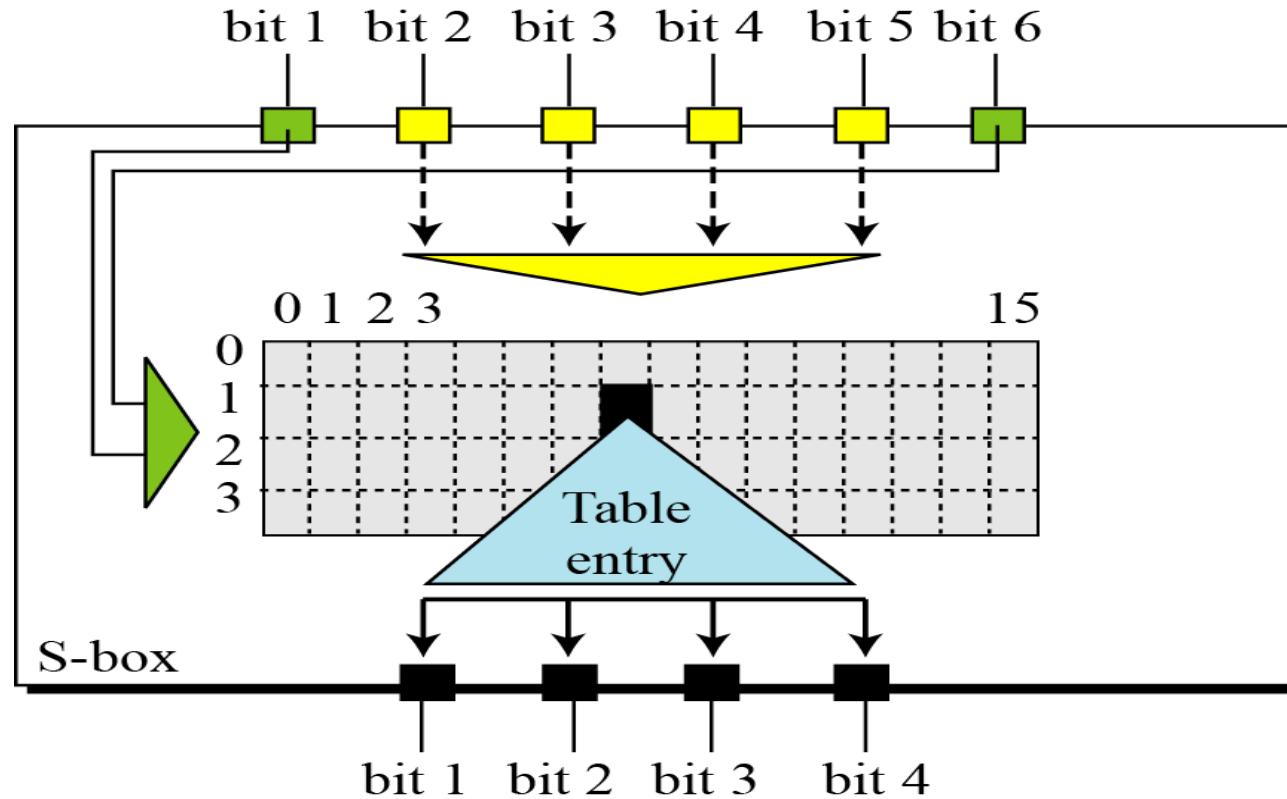
The S-boxes do the real mixing (confusion). DES uses 8 S-boxes, each with a 6-bit input and a 4-bit output. See Figure 6.7.

Figure 6.7 S-boxes



Continue

Figure 6.8 S-box rule



Continue

Table 6.3 shows the permutation for S-box 1. For the rest of the boxes see the textbook.

Table 6.3 S-box 1

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0	14	04	13	01	02	15	11	08	03	10	06	12	05	09	00	07
1	00	15	07	04	14	02	13	10	03	06	12	11	09	05	03	08
2	04	01	14	08	13	06	02	11	15	12	09	07	03	10	05	00
3	15	12	08	02	04	09	01	07	05	11	03	14	10	00	06	13

Continued

Example 6.3

The input to S-box 1 is **100011**. What is the output?

Solution

If we write the first and the sixth bits together, we get 11 in binary, which is 3 in decimal. The remaining bits are 0001 in binary, which is 1 in decimal. We look for the value in row 3, column 1, in Table 6.3 (S-box 1). The result is 12 in decimal, which in binary is 1100. So the input **100011** yields the output **1100**.

Continued

Example 6.4

The input to S-box 8 is 000000. What is the output?

Solution

If we write the first and the sixth bits together, we get 00 in binary, which is 0 in decimal. The remaining bits are 0000 in binary, which is 0 in decimal. We look for the value in row 0, column 0, in Table 6.10 (S-box 8). The result is 13 in decimal, which is 1101 in binary. So the input **000000** yields the output **1101**.

Continue

Straight Permutation

Table 6.11 Straight permutation table

16	07	20	21	29	12	28	17
01	15	23	26	05	18	31	10
02	08	24	14	32	27	03	09
19	13	30	06	22	11	04	25

Cipher and Reverse Cipher

Using mixers and swappers, we can create the cipher and reverse cipher, each having 16 rounds.

First Approach

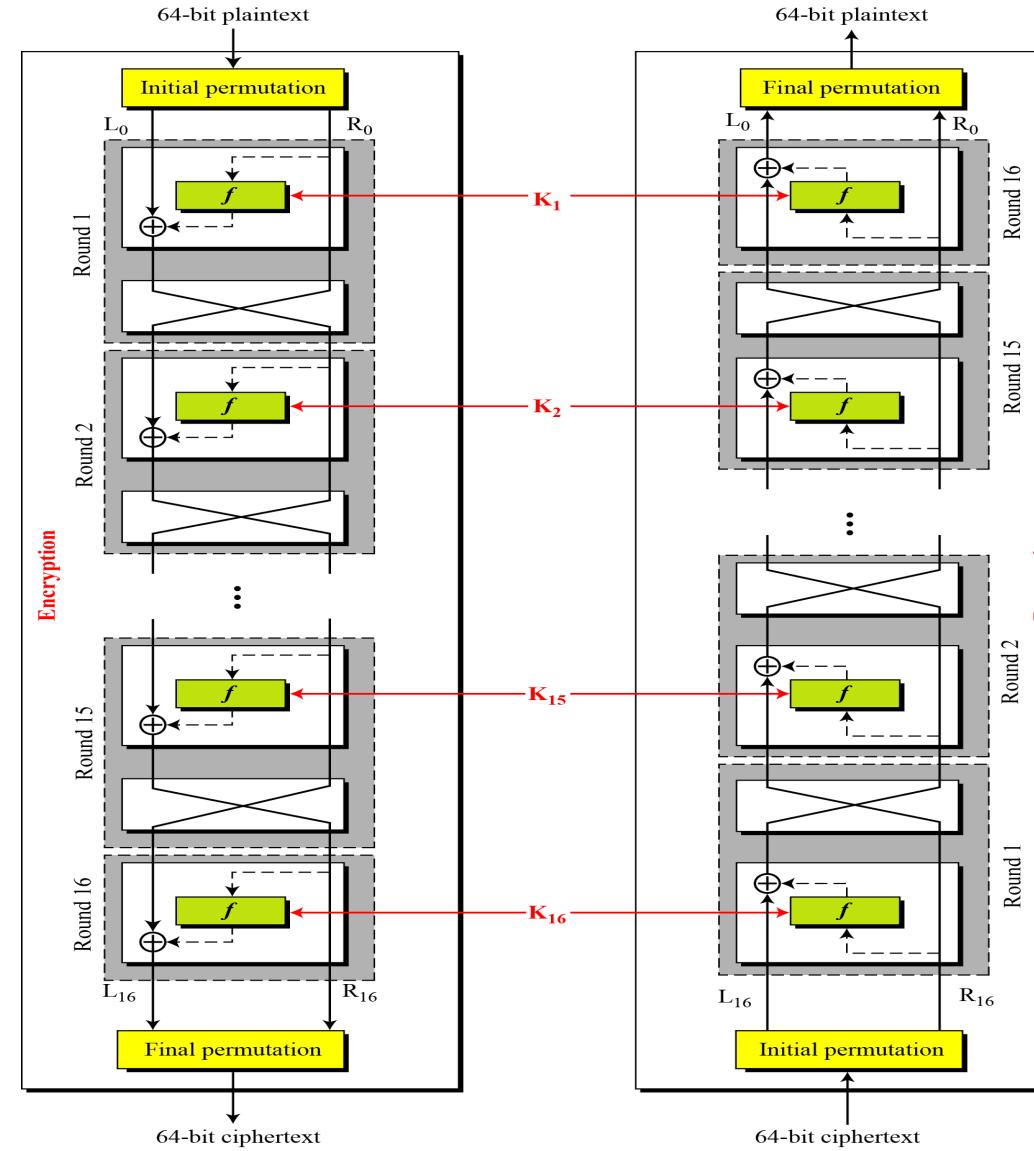
To achieve this goal, one approach is to make the last round (round 16) different from the others; it has only a mixer and no swapper.

Note

In the first approach, there is no swapper in the last round.

Continued

Figure DES cipher and reverse cipher for the first approach



6.2.3 Continued

Alternative Approach

We can make all 16 rounds the same by including one swapper to the 16th round and add an extra swapper after that (two swappers cancel the effect of each other).

Key Generation

The round-key generator creates sixteen 48-bit keys out of a 56-bit cipher key.

Continued

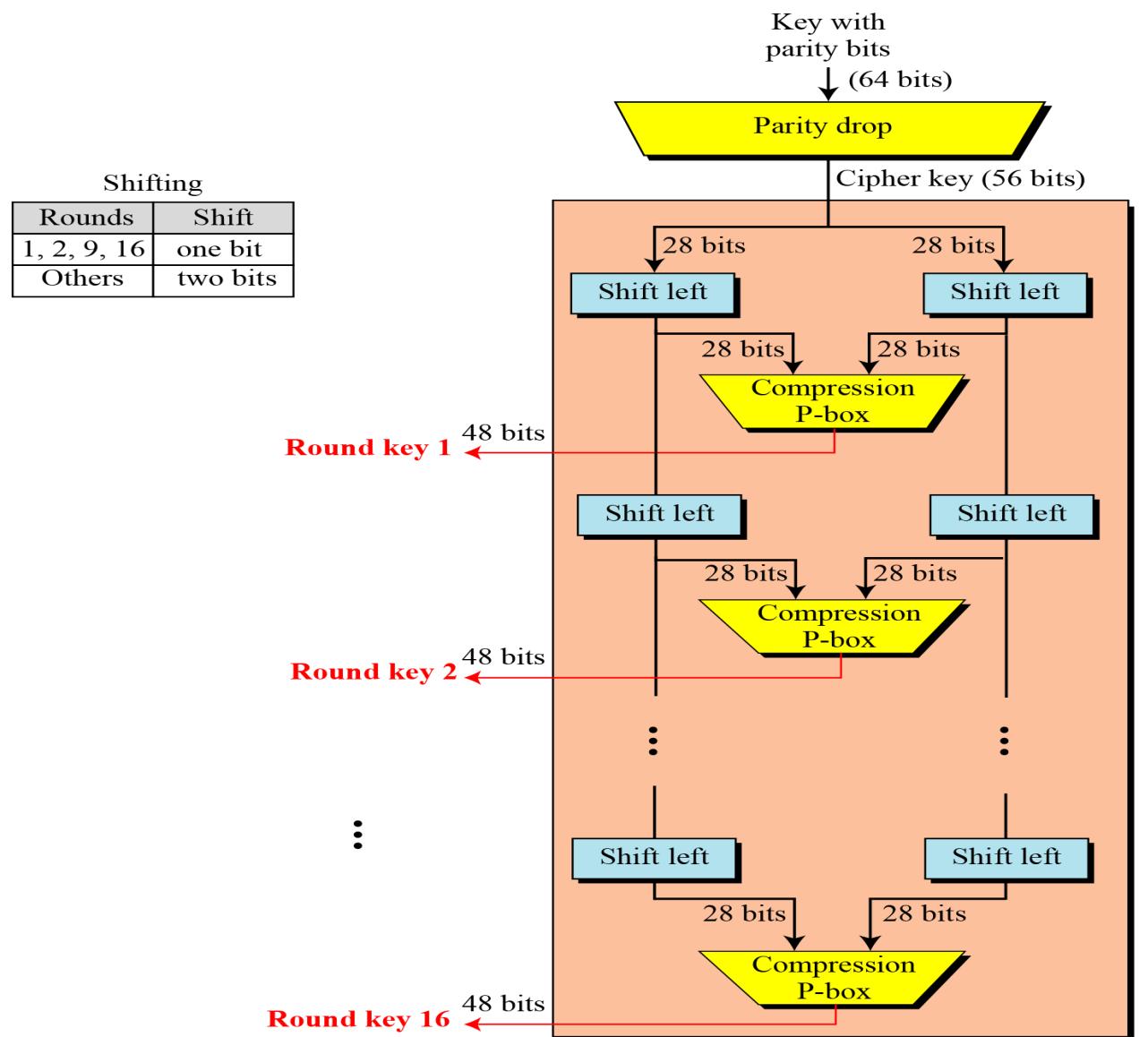


Figure 6.10
Key generation

Continued

Table 6.12 *Parity-bit drop table*

57	49	41	33	25	17	09	01
58	50	42	34	26	18	10	02
59	51	43	35	27	19	11	03
60	52	44	36	63	55	47	39
31	23	15	07	62	54	46	38
30	22	14	06	61	53	45	37
29	21	13	05	28	20	12	04

Table 6.13 *Number of bits shifts*

Round	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Bit shifts	1	1	2	2	2	2	2	2	1	2	2	2	2	2	2	1

Continued

Table 6.14 *Key-compression table*

14	17	11	24	01	05	03	28
15	06	21	10	23	19	12	04
26	08	16	07	27	20	13	02
41	52	31	37	47	55	30	40
51	45	33	48	44	49	39	56
34	53	46	42	50	36	29	32

Examples

Example 6.5

We choose a random plaintext block and a random key, and determine what the ciphertext block would be (all in hexadecimal):

Plaintext: 123456ABCD132536

Key: AABB09182736CCDD

CipherText: C0B7A8D05F3A829C

Table 6.15 Trace of data for Example 6.5

Plaintext: 123456ABCD132536			
After initial permutation: 14A7D67818CA18AD			
After splitting: $L_0 = 14A7D678$ $R_0 = 18CA18AD$			
Round	Left	Right	Round Key
Round 1	18CA18AD	5A78E394	194CD072DE8C
Round 2	5A78E394	4A1210F6	4568581ABCCE
Round 3	4A1210F6	B8089591	06EDA4ACF5B5
Round 4	B8089591	236779C2	DA2D032B6EE3

6.2.4 Continued

Example 6.5

Continued

Table 6.15 Trace of data for Example 6.5 (Conintued)

<i>Round 5</i>	236779C2	A15A4B87	69A629FEC913
<i>Round 6</i>	A15A4B87	2E8F9C65	C1948E87475E
<i>Round 7</i>	2E8F9C65	A9FC20A3	708AD2DDB3C0
<i>Round 8</i>	A9FC20A3	308BEE97	34F822F0C66D
<i>Round 9</i>	308BEE97	10AF9D37	84BB4473DCCC
<i>Round 10</i>	10AF9D37	6CA6CB20	02765708B5BF
<i>Round 11</i>	6CA6CB20	FF3C485F	6D5560AF7CA5
<i>Round 12</i>	FF3C485F	22A5963B	C2C1E96A4BF3
<i>Round 13</i>	22A5963B	387CCDAA	99C31397C91F
<i>Round 14</i>	387CCDAA	BD2DD2AB	251B8BC717D0
<i>Round 15</i>	BD2DD2AB	CF26B472	3330C5D9A36D
<i>Round 16</i>	19BA9212	CF26B472	181C5D75C66D
<i>After combination:</i> 19BA9212CF26B472			
<i>Ciphertext:</i> C0B7A8D05F3A829C		<i>(after final permutation)</i>	

6.2.4 Continued

Example 6.6

Let us see how Bob, at the destination, can decipher the ciphertext received from Alice using the same key. Table 6.16 shows some interesting points.

Ciphertext: C0B7A8D05F3A829C			
<i>After initial permutation:</i> 19BA9212CF26B472			
After splitting: $L_0=19BA9212 \quad R_0=CF26B472$			
Round	Left	Right	Round Key
Round 1	CF26B472	BD2DD2AB	181C5D75C66D
Round 2	BD2DD2AB	387CCDAA	3330C5D9A36D
...
Round 15	5A78E394	18CA18AD	4568581ABCCE
Round 16	14A7D678	18CA18AD	194CD072DE8C
After combination: 14A7D67818CA18AD			
Plaintext: 123456ABCD132536		(after final permutation)	

Strength of DES – Key Size

- 56-bit keys have $2^{56} = 7.2 \times 10^{16}$ values
- brute force search looks hard
- recent advances have shown is possible
 - in 1997 on Internet in a few months
 - in 1998 on dedicated h/w (EFF) in a few days
 - in 1999 above combined in 22hrs!
- still must be able to recognize plaintext
- now considering alternatives to DES

Strength of DES – Timing Attacks

- attacks actual implementation of cipher
- use knowledge of consequences of implementation to derive knowledge of some/all subkey bits
- specifically use fact that calculations can take varying times depending on the value of the inputs to it
- particularly problematic on smartcards

Strength of DES – Analytic Attacks

- now have several analytic attacks on DES
- these utilise some deep structure of the cipher
 - by gathering information about encryptions
 - can eventually recover some/all of the sub-key bits
 - if necessary then exhaustively search for the rest
- generally these are statistical attacks
- include
 - differential cryptanalysis
 - linear cryptanalysis
 - related key attacks

Example 6.8

Let us try the first weak key in Table 6.18 to encrypt a block two times. After two encryptions

with the same key the original plaintext block is created. Note that we have used the encryption algorithm two times, not one encryption followed by another decryption.

Key: 0x0101010101010101

Plaintext: 0x1234567887654321

Ciphertext: 0x814FE938589154F7

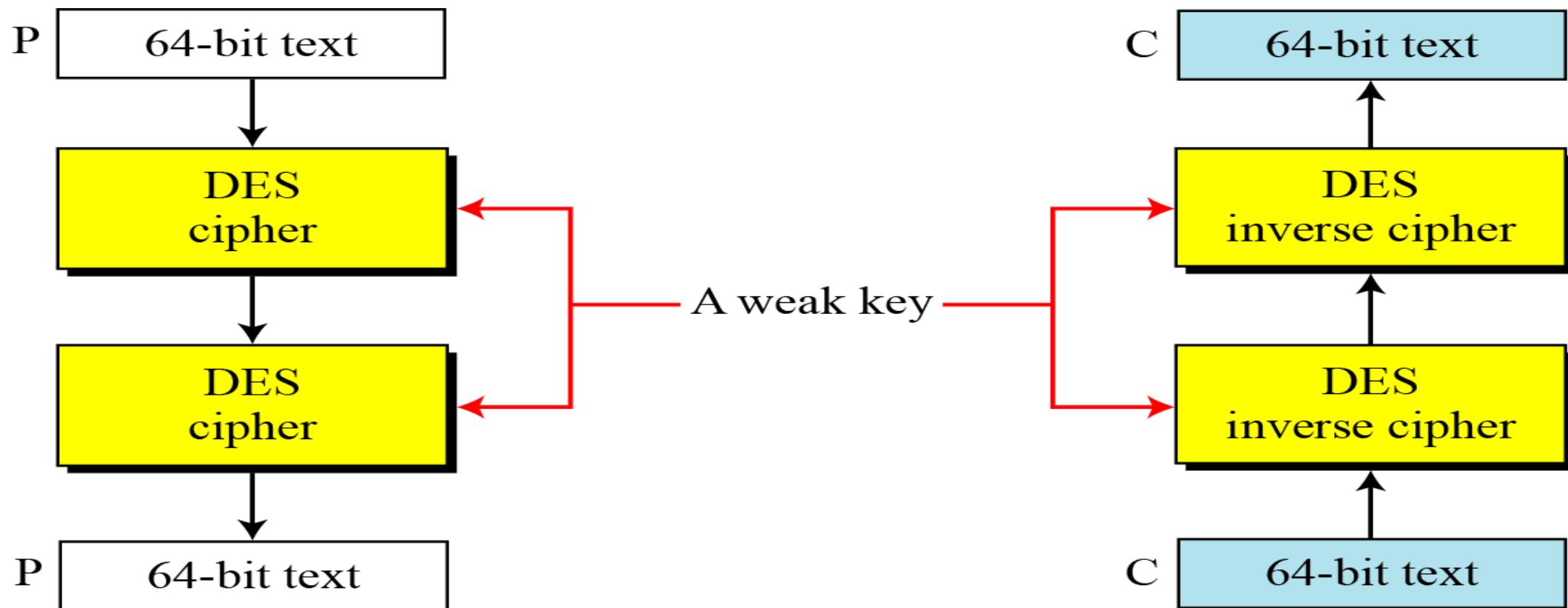
Key: 0x0101010101010101

Plaintext: 0x814FE938589154F7

Ciphertext: 0x1234567887654321

Continued

Figure 6.11 Double encryption and decryption with a weak key



Continued

Table 6.19 *Semi-weak keys*

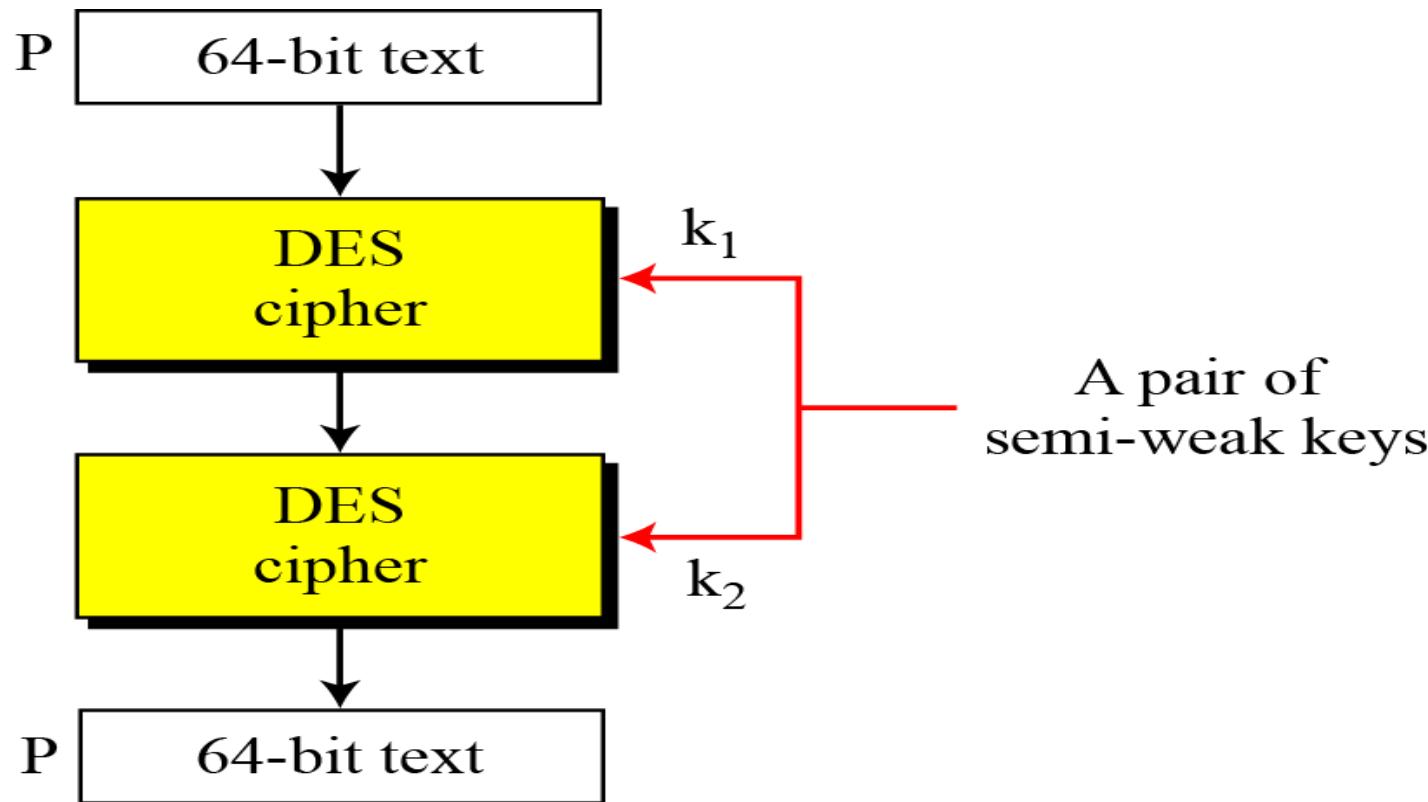
<i>First key in the pair</i>	<i>Second key in the pair</i>
01FE 01FE 01FE 01FE	FE01 FE01 FE01 FE01
1FEO 1FEO OEF1 OEF1	E01F E01F F10E F10E
01EO 01E1 01F1 01F1	E001 E001 F101 F101
1FFE 1FFE OEFFE OEFFE	FE1F FE1F FEOE FEOE
011F 011F 010E 010E	1F01 1F01 OE01 OE01
EOF EEOF F1FE F1FE	FEE0 FEE0 FEF1 FEF1

6.3.3 *Continued*

<i>Round key 1</i>	9153E54319BD	6EAC1ABCE642
<i>Round key 2</i>	6EAC1ABCE642	9153E54319BD
<i>Round key 3</i>	6EAC1ABCE642	9153E54319BD
<i>Round key 4</i>	6EAC1ABCE642	9153E54319BD
<i>Round key 5</i>	6EAC1ABCE642	9153E54319BD
<i>Round key 6</i>	6EAC1ABCE642	9153E54319BD
<i>Round key 7</i>	6EAC1ABCE642	9153E54319BD
<i>Round key 8</i>	6EAC1ABCE642	9153E54319BD
<i>Round key 9</i>	9153E54319BD	6EAC1ABCE642
<i>Round key 10</i>	9153E54319BD	6EAC1ABCE642
<i>Round key 11</i>	9153E54319BD	6EAC1ABCE642
<i>Round key 12</i>	9153E54319BD	6EAC1ABCE642
<i>Round key 13</i>	9153E54319BD	6EAC1ABCE642
<i>Round key 14</i>	9153E54319BD	6EAC1ABCE642
<i>Round key 15</i>	9153E54319BD	6EAC1ABCE642
<i>Round key 16</i>	6EAC1ABCE642	9153E54319BD

6.3.3 Continued

Figure 6.12 A pair of semi-weak keys in encryption and decryption



6.3.3 *Continued*

Example 6.9

What is the probability of randomly selecting a weak, a semi-weak, or a possible weak key?

Solution

DES has a key domain of 2^{56} . The total number of the above keys are 64 ($4 + 12 + 48$). The probability of choosing one of these keys is 8.8×10^{-16} , almost impossible.

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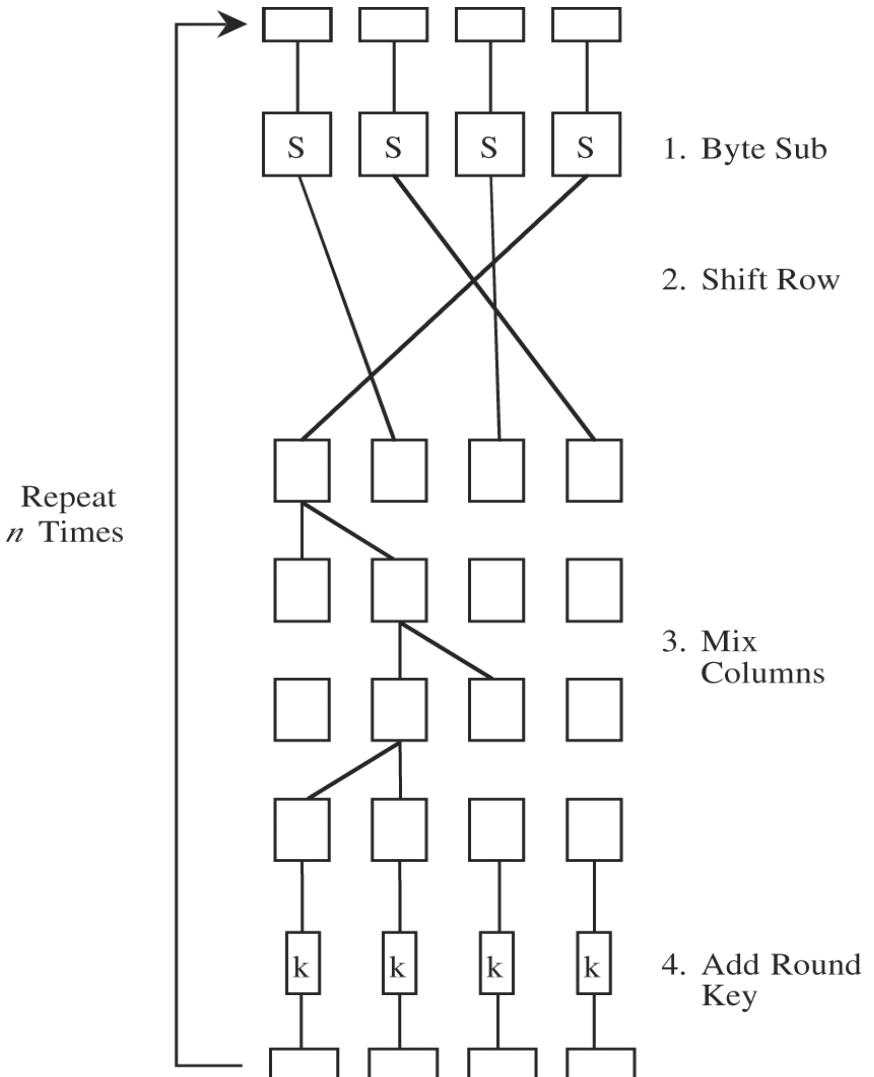
Key Complement In the key domain (2^{56}), definitely half of the keys are *complement* of the other half. A **key complement** can be made by inverting (changing 0 to 1 or 1 to 0) each bit in the key. Does a key complement simplify the job of the cryptanalysis? It happens that it does. Eve can use only half of the possible keys (2^{55}) to perform brute-force attack. This is because

$$C = E(K, P) \rightarrow \bar{C} = E(\bar{K}, \bar{P})$$

In other words, if we encrypt the complement of plaintext with the complement of the key, we get the complement of the ciphertext. Eve does not have to test all 2^{56} possible keys, she can test only half of them and then complement the result.

AES: Advanced Encryption System

- Symmetric block cipher
- Developed in 1999 by independent Dutch cryptographers
- Still in common use



DES vs. AES

	DES	AES
Date designed	1976	1999
Block size	64 bits	128 bits
Key length	56 bits (effective length); up to 112 bits with multiple keys	128, 192, 256 (and possibly more) bits
Operations	16 rounds	10, 12, 14 (depending on key length); can be increased
Encryption primitives	Substitution, permutation	Substitution, shift, bit mixing
Cryptographic primitives	Confusion, diffusion	Confusion, diffusion
Design	Open	Open
Design rationale	Closed	Open
Selection process	Secret	Secret, but open public comments and criticisms invited
Source	IBM, enhanced by NSA	Independent Dutch cryptographers

Public Key (Asymmetric) Cryptography

- Instead of two users sharing one secret key, each user has two keys: one public and one private
- Messages encrypted using the user's public key can only be decrypted using the user's private key, and vice versa

Secret Key vs. Public Key Encryption

	Secret Key (Symmetric)	Public Key (Asymmetric)
Number of keys	1	2
Key size (bits)	56–112 (DES), 128–256 (AES)	Unlimited; typically no less than 256; 1000 to 2000 currently considered desirable for most uses
Protection of key	Must be kept secret	One key must be kept secret; the other can be freely exposed
Best uses	Cryptographic workhorse. Secrecy and integrity of data, from single characters to blocks of data, messages and files	Key exchange, authentication, signing
Key distribution	Must be out-of-band	Public key can be used to distribute other keys
Speed	Fast	Slow, typically by a factor of up to 10,000 times slower than symmetric algorithms

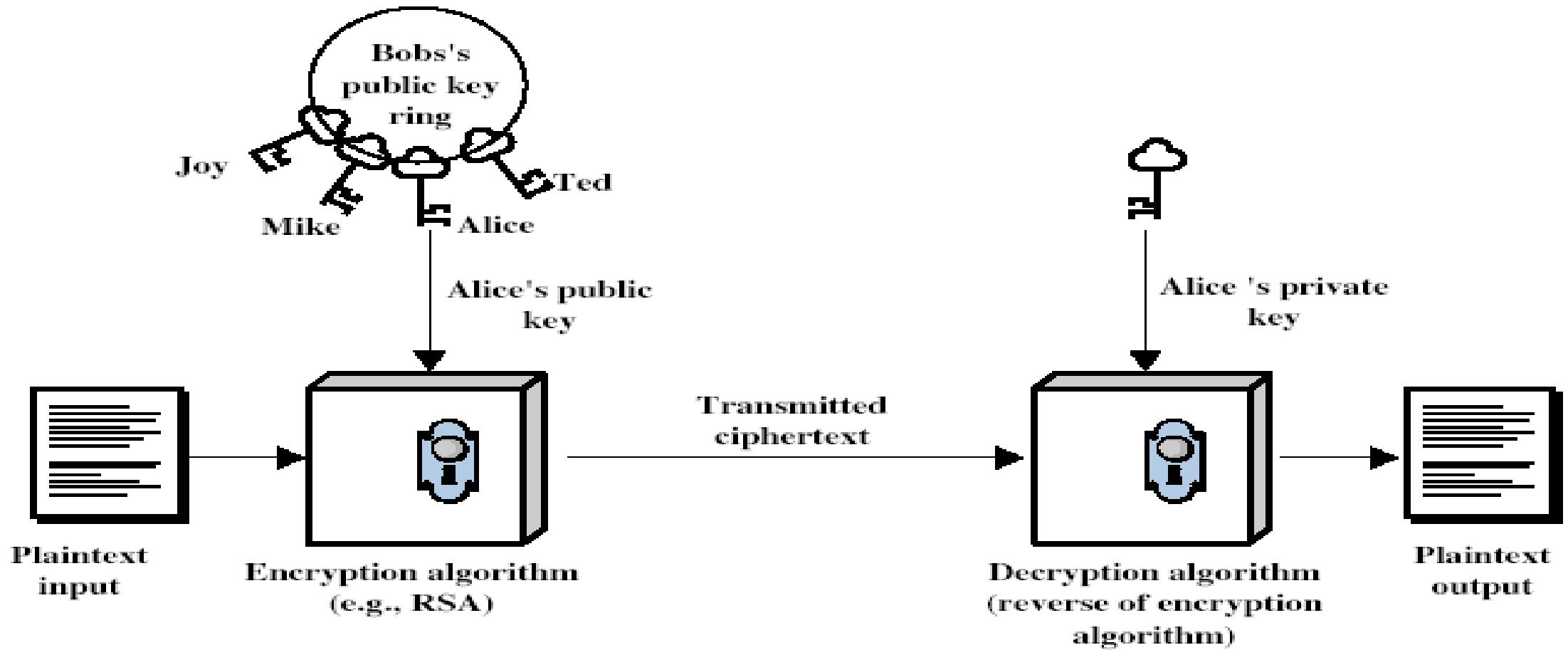
Public-Key Cryptography

- probably most significant advance in the 3000 year history of cryptography
- uses **two** keys – a public & a private key
- **asymmetric** since parties are **not** equal
- uses clever application of number theoretic concepts to function
- complements **rather than** replaces private key crypto

Public-Key Cryptography

- **public-key/two-key/asymmetric** cryptography involves the use of **two keys**:
 - a **public-key**, which may be known by anybody, and can be used to **encrypt messages**, and **verify signatures**
 - a **private-key**, known only to the recipient, used to **decrypt messages**, and **sign (create) signatures**
- is **asymmetric** because
 - those who encrypt messages or verify signatures **cannot** decrypt messages or create signatures

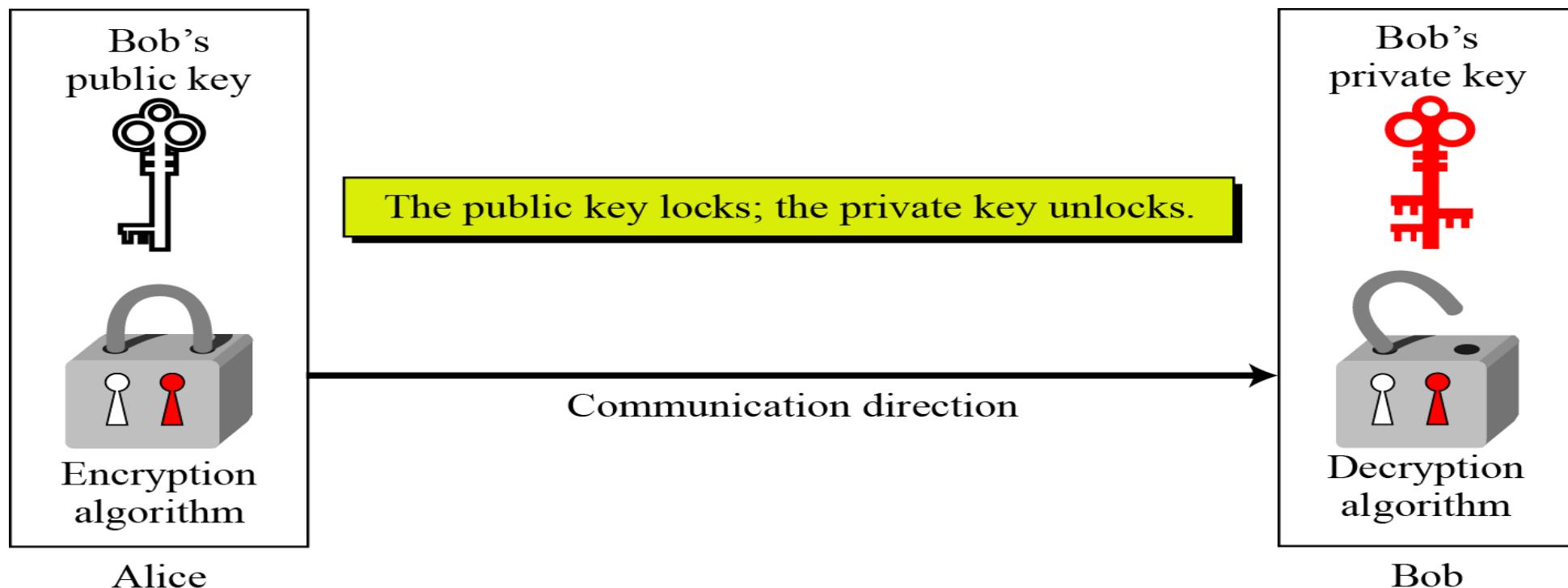
Public-Key Cryptography



Keys

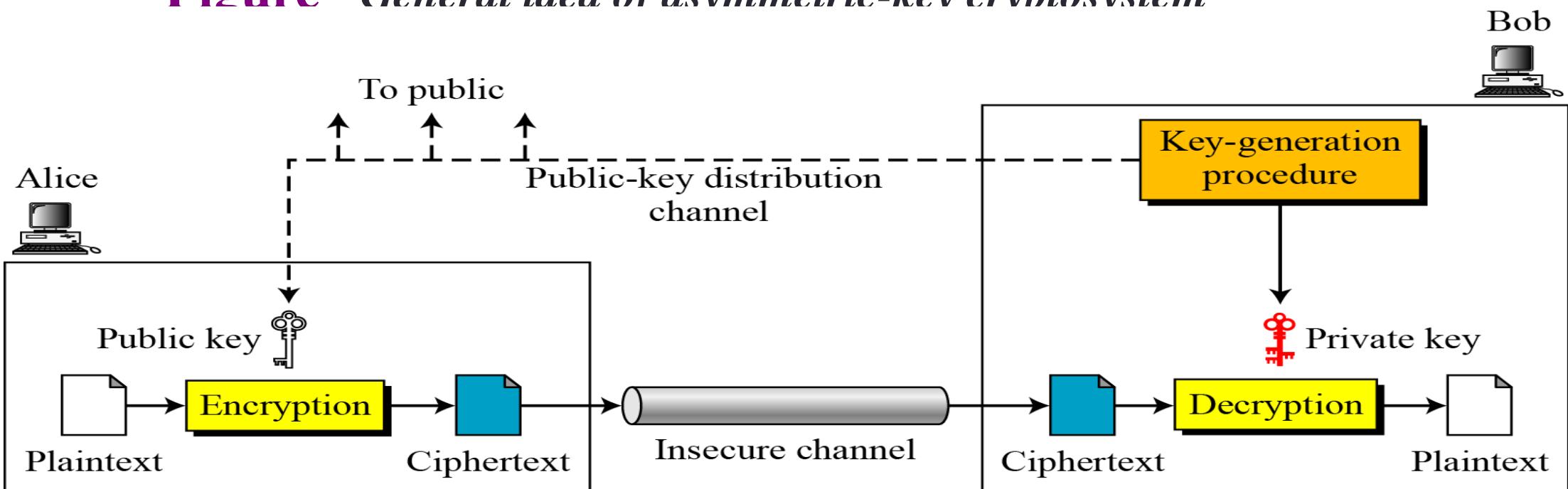
Asymmetric key cryptography uses two separate keys: one private and one public.

Figure Locking and unlocking in asymmetric-key cryptosystem



General Idea

Figure *General idea of a symmetric-key crypto system*



Why Public-Key Cryptography?

- developed to address two key issues:
 - **key distribution** – how to have secure communications in general without having to trust a KDC with your key
 - **digital signatures** – how to verify a message comes intact from the claimed sender
- public invention due to Whitfield Diffie & Martin Hellman at Stanford Uni in 1976
 - known earlier in classified community

Public-Key Characteristics

- Public-Key algorithms rely on two keys with the characteristics that it is:
 - computationally infeasible to find decryption key knowing only algorithm & encryption key
 - computationally easy to en/decrypt messages when the relevant (en/decrypt) key is known
 - either of the two related keys can be used for encryption, with the other used for decryption (in some schemes)

Public-Key Cryptosystems

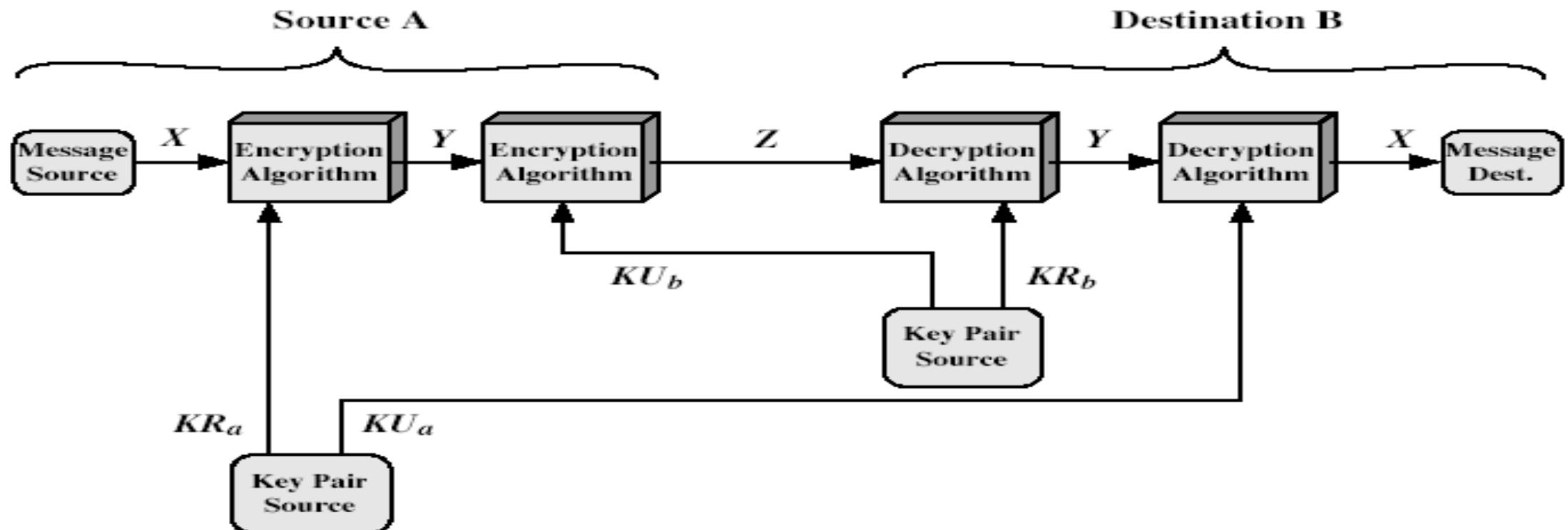
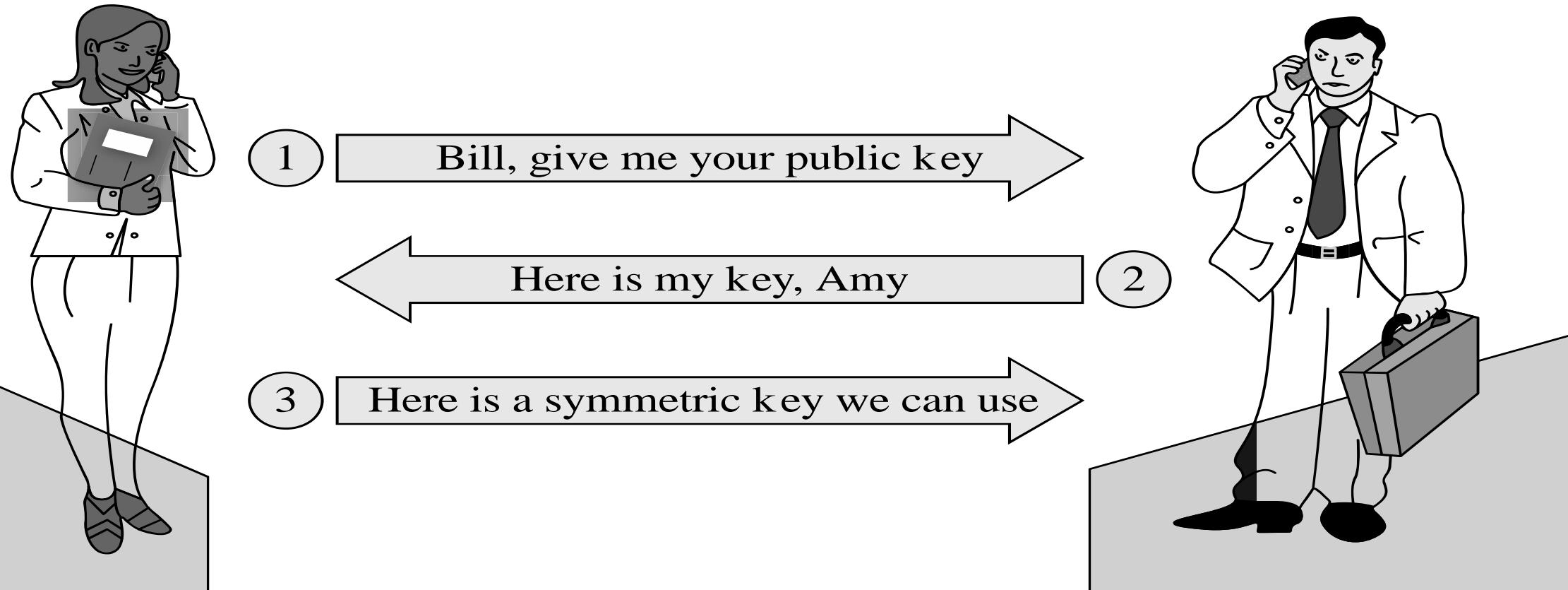


Figure 9.4 Public-Key Cryptosystem: Secrecy and Authentication

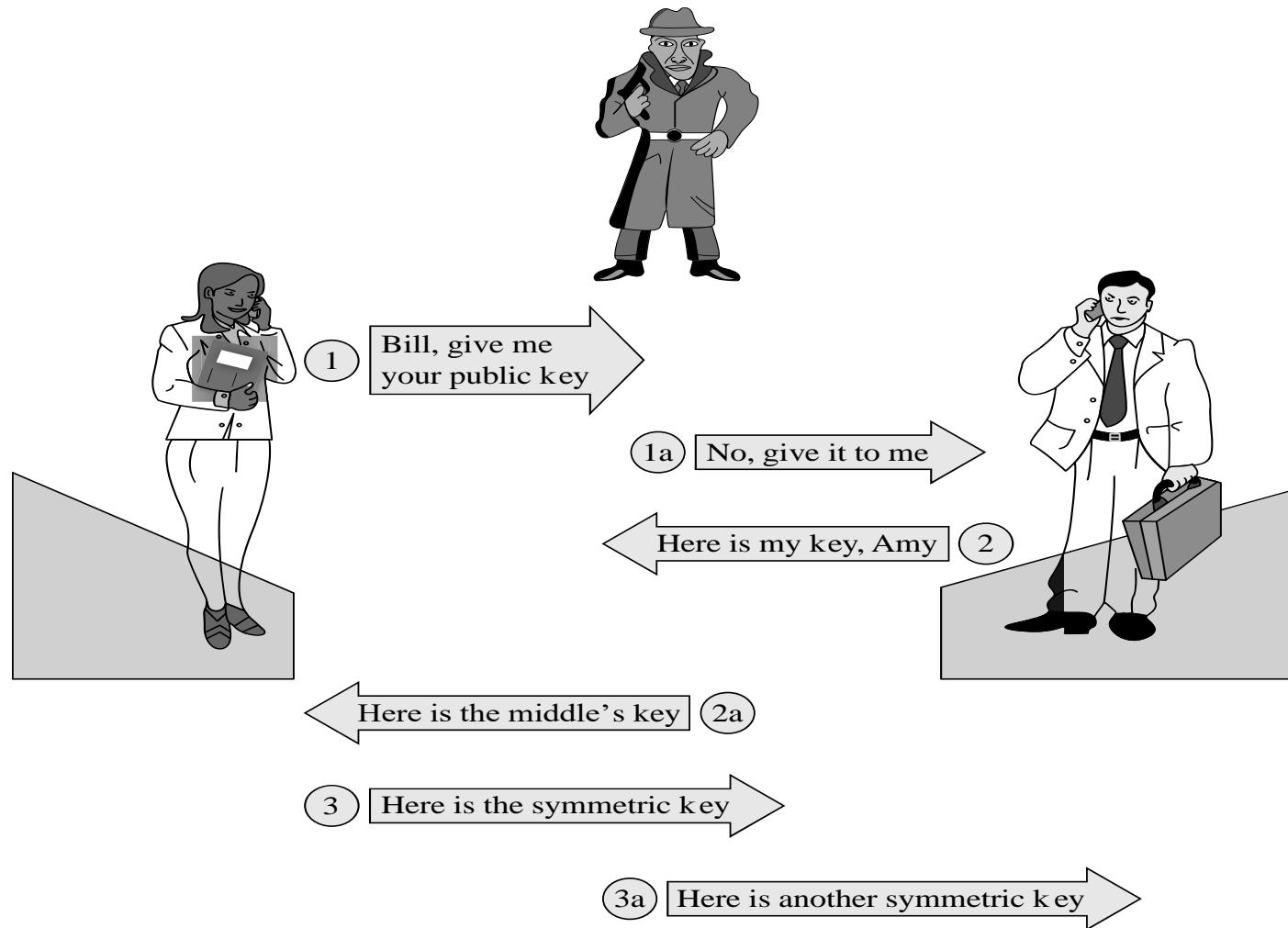
Public-Key Applications

- can classify uses into 3 categories:
 - **encryption/decryption** (provide secrecy)
 - **digital signatures** (provide authentication)
 - **key exchange** (of session keys)
- some algorithms are suitable for all uses, others are specific to one

Public Key to Exchange Secret Keys



Key Exchange Man in the Middle



Man-in-the-middle attack

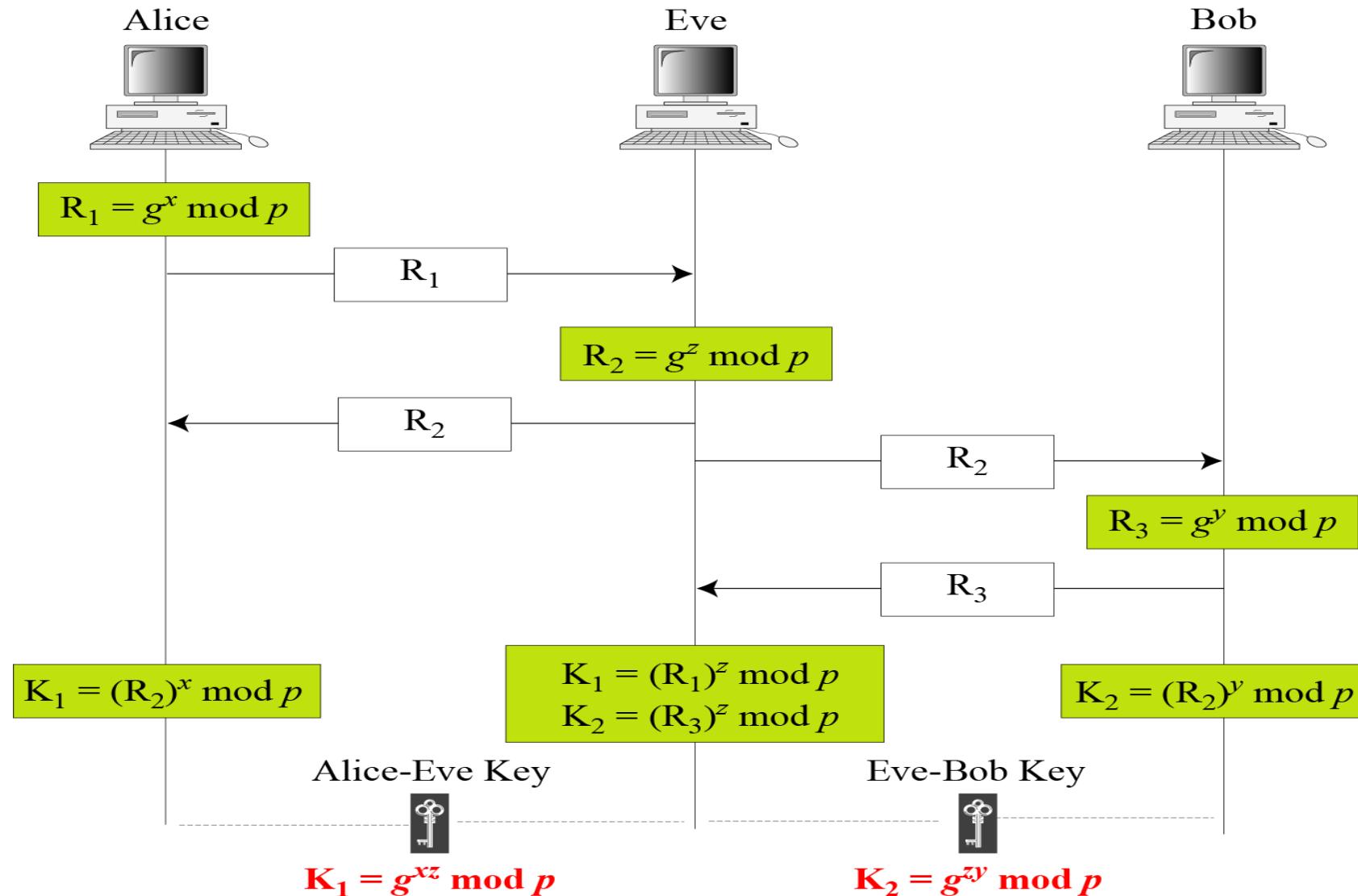
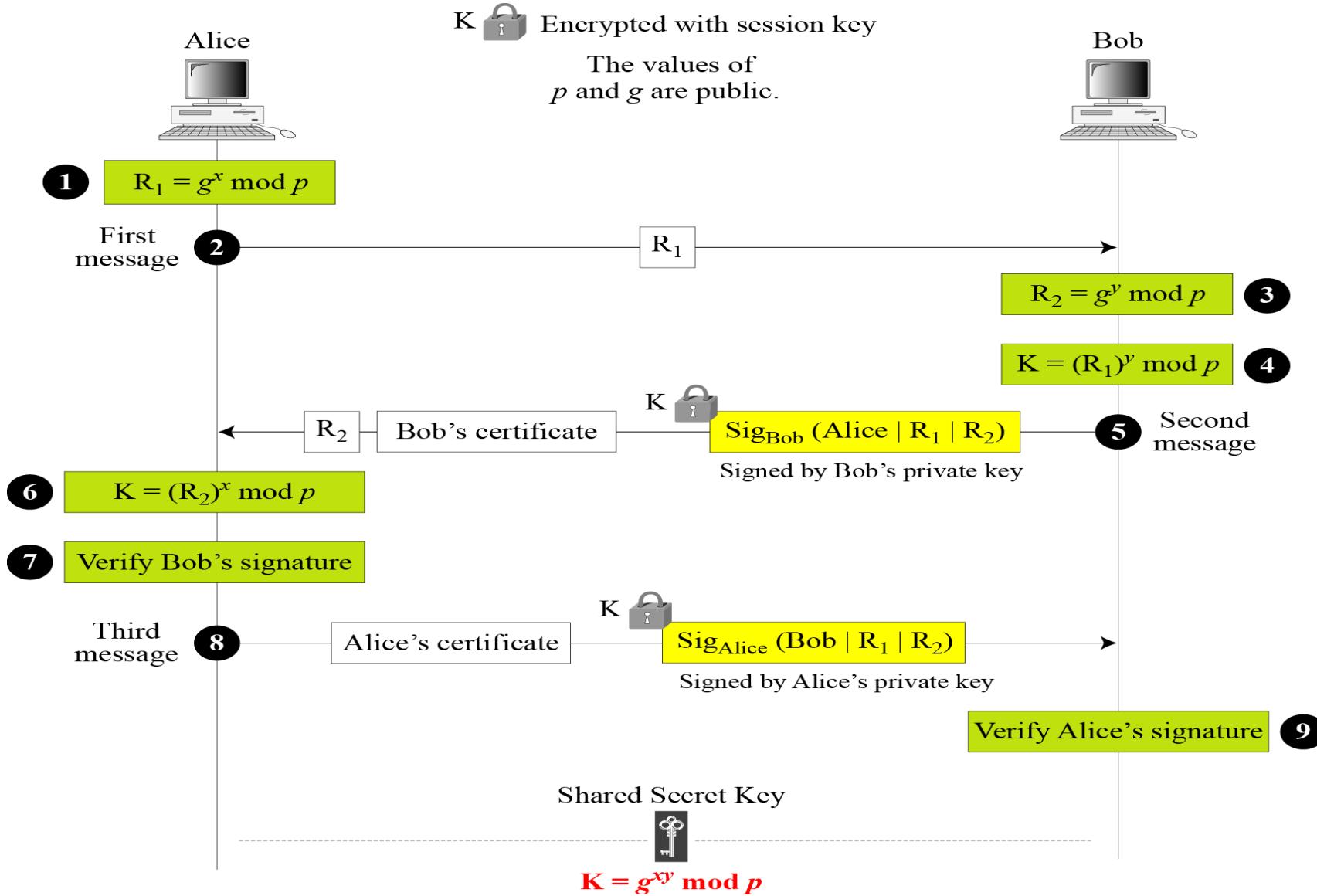


Figure Station-to-station key agreement method



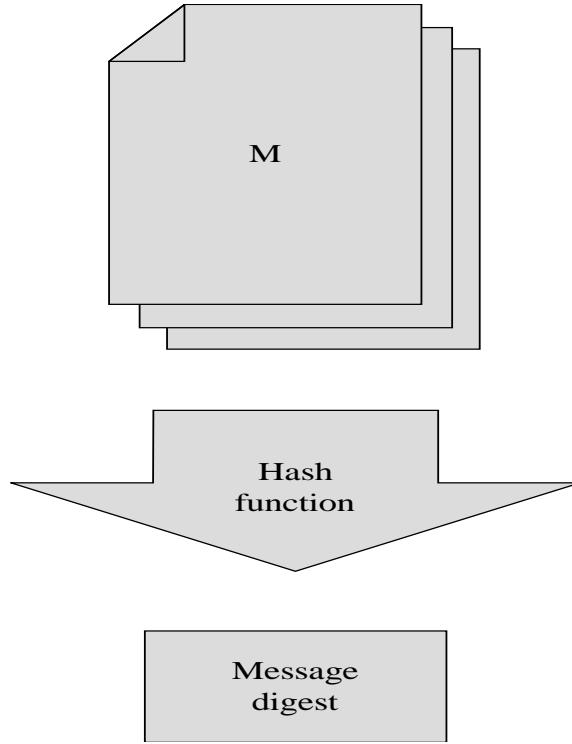
Error Detecting Codes

- Demonstrates that a block of data has been modified
- Simple error detecting codes:
 - Parity checks
 - Cyclic redundancy checks
- Cryptographic error detecting codes:
 - One-way hash functions
 - Cryptographic checksums
 - Digital signatures

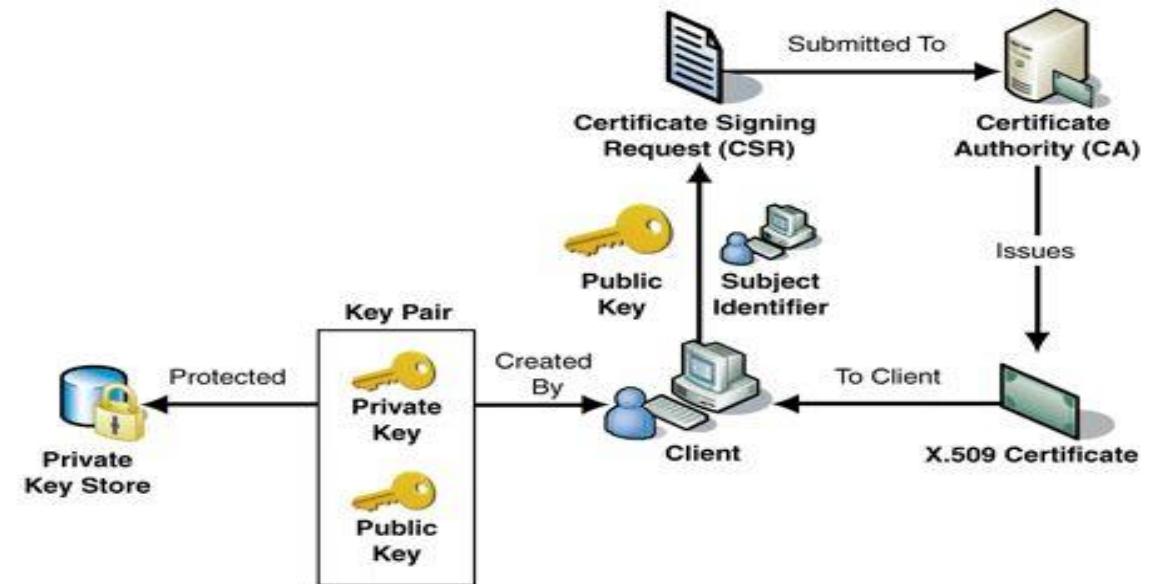
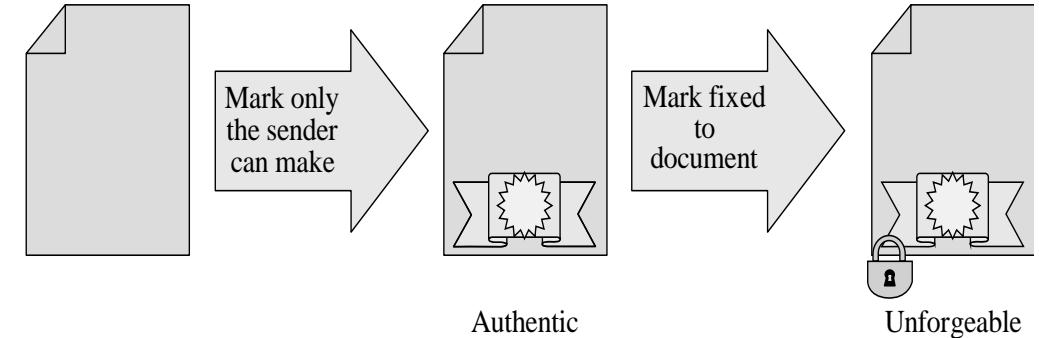
Original Data	Parity Bit	Modified Data	Modification Detected?
0 0 0 0 0 0 0 0	1	0 0 0 0 0 0 0 <u>1</u>	Yes
0 0 0 0 0 0 0 0	1	<u>1</u> 0 0 0 0 0 0 0	Yes
0 0 0 0 0 0 0 0	1	<u>1</u> 0 0 0 0 0 0 <u>1</u>	No
0 0 0 0 0 0 0 0	1	0 0 0 0 0 0 <u>1</u> <u>1</u>	No
0 0 0 0 0 0 0 0	1	0 0 0 0 0 <u>1</u> <u>1</u> <u>1</u>	Yes
0 0 0 0 0 0 0 0	1	0 0 0 0 <u>1</u> <u>1</u> <u>1</u> <u>1</u>	No
0 0 0 0 0 0 0 0	1	0 <u>1</u> 0 <u>1</u> 0 <u>1</u> 0 <u>1</u>	No
0 0 0 0 0 0 0 0	1	<u>1</u> <u>1</u> <u>1</u> <u>1</u> <u>1</u> <u>1</u> <u>1</u>	No

Parity Check

One-Way Hash Function

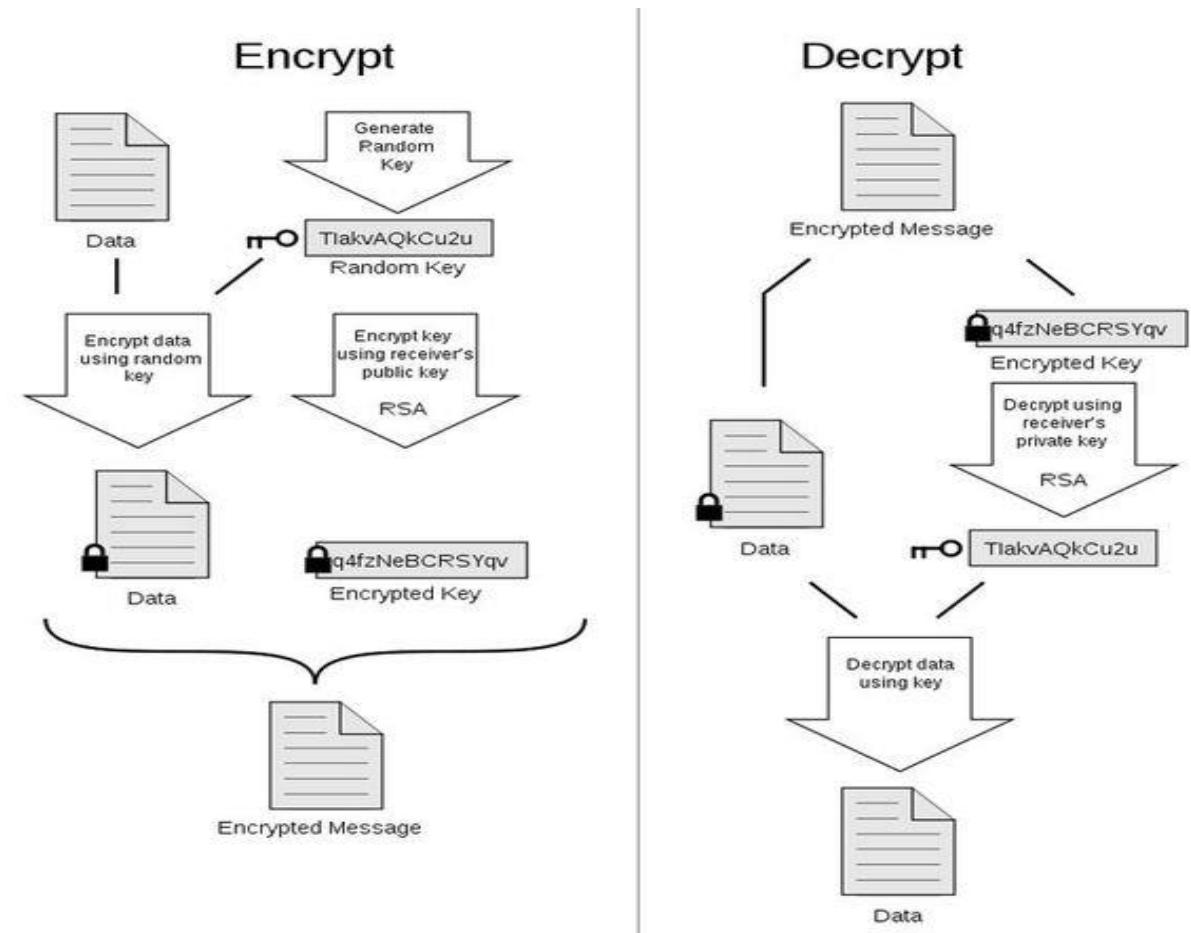


Digital Signature



Certificates: Trustable Identities and Public Keys

- A certificate is a public key and an identity bound together and signed by a certificate authority.
- A certificate authority is an authority that users trust to accurately verify identities before generating certificates that bind those identities to keys.



Certificate Signing and Hierarchy

To create Diana's certificate:

Diana creates and delivers to Edward:

Name: Diana
Position: Division Manager
Public key: 17EF83CA ...

Edward adds:

Name: Diana	hash value 128C4
Position: Division Manager	
Public key: 17EF83CA ...	

Edward signs with his private key:

Name: Diana	hash value 128C4
Position: Division Manager	
Public key: 17EF83CA ...	

Which is Diana's certificate.

To create Delwyn's certificate:

Delwyn creates and delivers to Diana:

Name: Delwyn
Position: Dept Manager
Public key: 3AB3882C ...

Diana adds:

Name: Delwyn	hash value 48CFA
Position: Dept Manager	
Public key: 3AB3882C ...	

Diana signs with her private key:

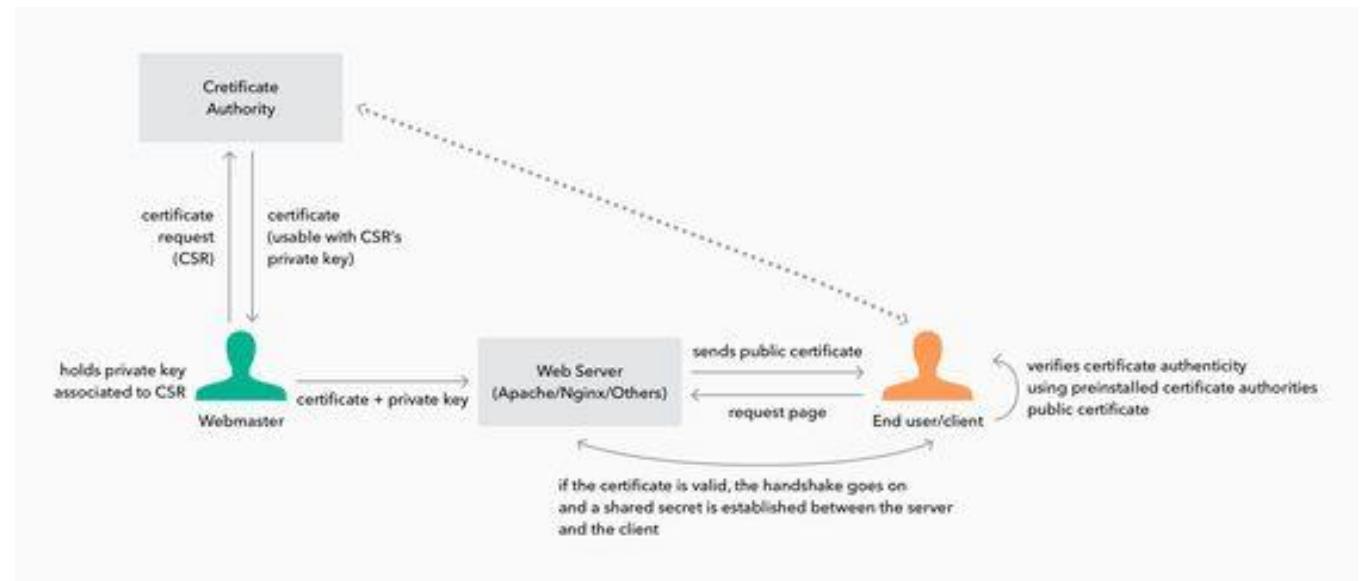
Name: Delwyn	hash value 48CFA
Position: Dept Manager	
Public key: 3AB3882C ...	

And appends her certificate:

Name: Delwyn	hash value 48CFA
Position: Dept Manager	
Public key: 3AB3882C ...	
Name: Diana	hash value 128C4

Which is Delwyn's certificate.

Diana's certificate is made using Edward's signature.
 Delwyn's certificate includes Diana's certificate so that it can effectively be tied back to Edward, creating a chain of trust.

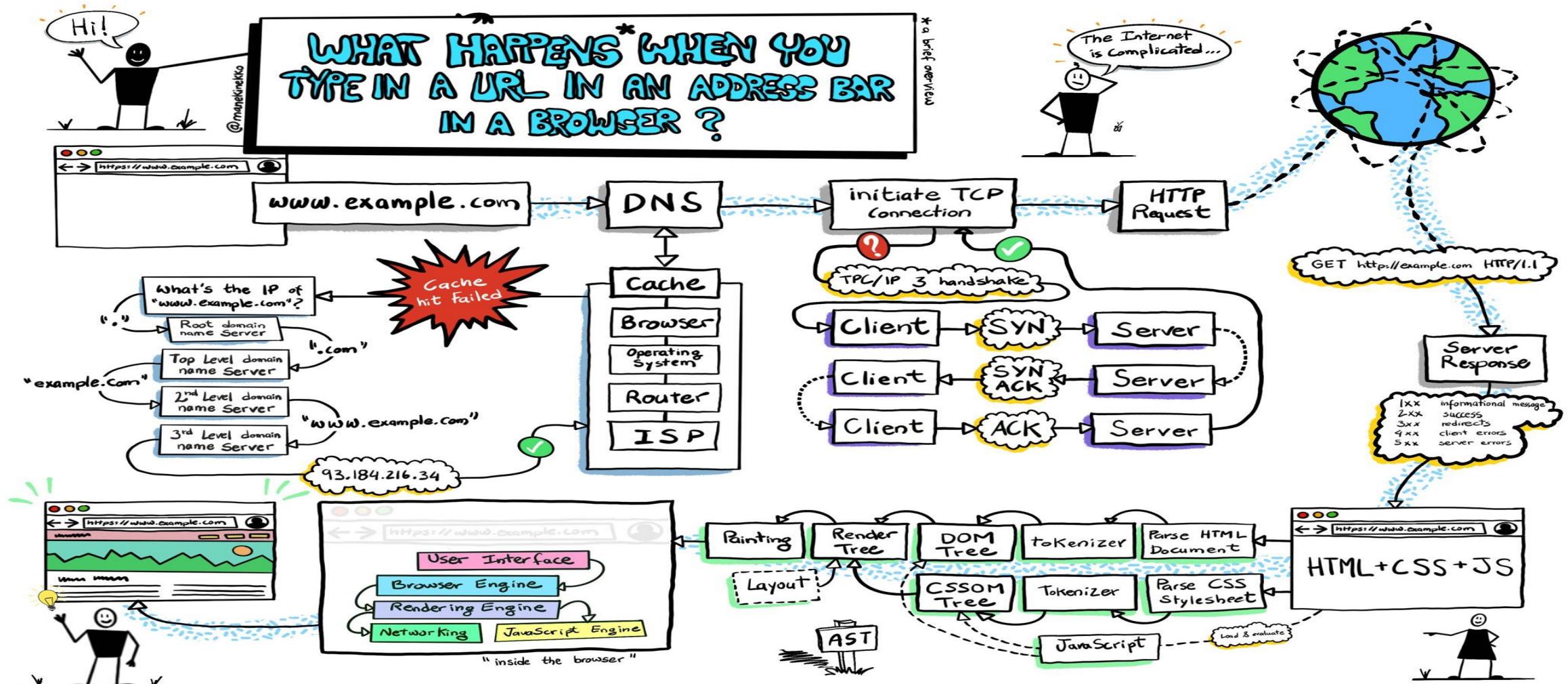


HTTPS helps greatly in reducing the information leaked to third parties. However, it does not prevent tracking. Modern browser fingerprinting techniques work even behind HTTPS. Security researchers have developed a browser extension called HTTPS Everywhere that attempts to use HTTPS whenever possible and at the same time mitigate the use of fingerprinting techniques.

Cryptographic Tool Summary

Tool	Uses
Secret key (symmetric) encryption	Protecting confidentiality and integrity of data at rest or in transit
Public key (asymmetric) encryption	Exchanging (symmetric) encryption keys Signing data to show authenticity and proof of origin
Error detection codes	Detect changes in data
Hash codes and functions (forms of error detection codes)	Detect changes in data
Cryptographic hash functions	Detect changes in data, using a function that only the data owner can compute (so an outsider cannot change both data and the hash code result to conceal the fact of the change)
Error correction codes	Detect and repair errors in data
Digital signatures	Attest to the authenticity of data
Digital certificates	Allow parties to exchange cryptographic keys with confidence of the identities of both parties

What happens with URLs?



Summary

- Encryption helps prevent attackers from revealing, modifying, or fabricating messages
- Symmetric and asymmetric encryption have complementary strengths and weaknesses
- Certificates bind identities to digital signatures