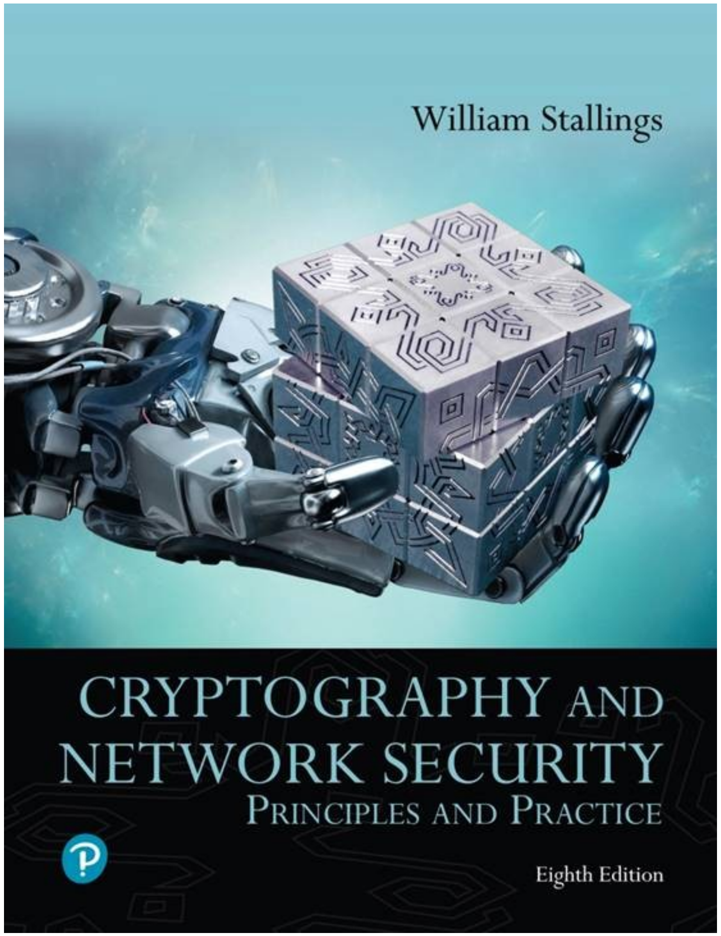
Cryptography and Network Security: Principles and Practice

Eighth Edition



Chapter 3

Classical Encryption Techniques

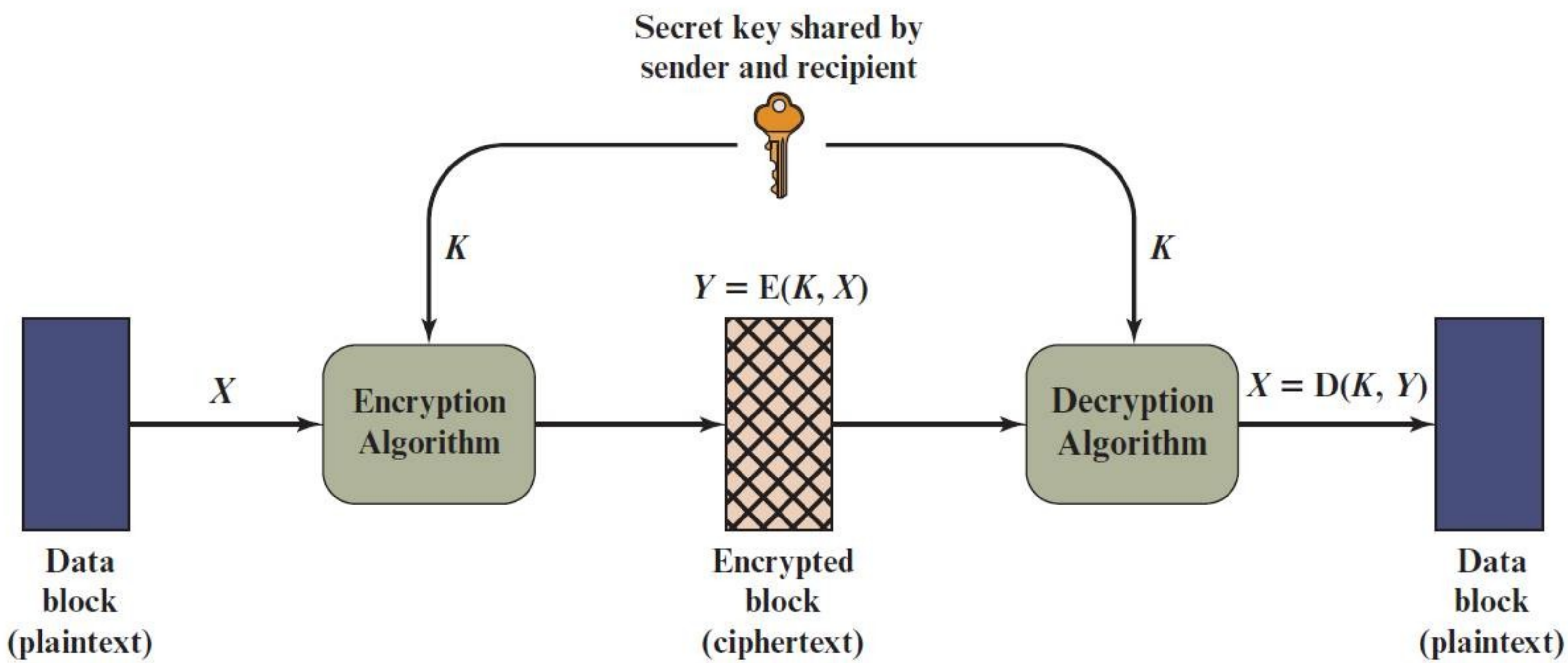
Definitions (1 of 2)

- Plaintext
  - An original message
- Ciphertext
  - The coded message
- Enciphering/encryption
  - The process of converting from plaintext to ciphertext
- Deciphering/decryption
  - Restoring the plaintext from the ciphertext

Definitions (2 of 2)

- Cryptography
  - The area of study of the many schemes used for encryption
- Cryptographic system/cipher
  - A scheme
- Cryptanalysis
  - Techniques used for deciphering a message without any knowledge of the enciphering details
- Cryptology
  - The areas of cryptography and cryptanalysis

Figure 3.1 Simplified Model of Symmetric Encryption

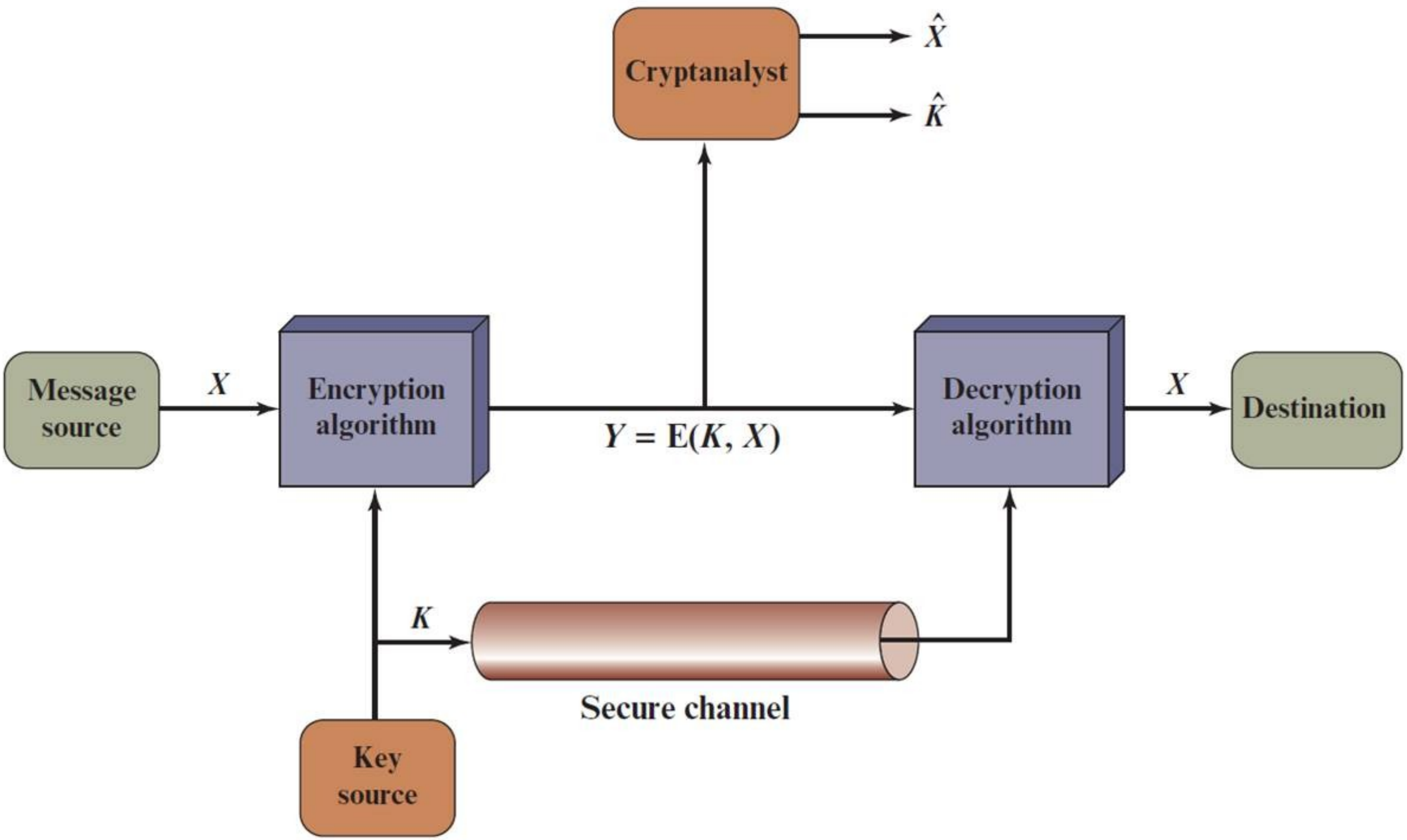


Pearson

Symmetric Cipher Model

- There are two requirements for secure use of conventional encryption:
  - A strong encryption algorithm
  - Sender and receiver must have obtained copies of the secret key in a secure fashion and must keep the key secure

Figure 3.2 Model of Symmetric Cryptosystem



Cryptographic Systems

- Characterized along three independent dimensions:
- The type of operations used for transforming plaintext to ciphertext
  - Substitution
  - Transposition
- The number of keys used
  - Symmetric, single-key, secret-key, conventional encryption
  - Asymmetric, two-key, or public-key encryption
- The way in which the plaintext is processed
  - Block cipher
  - Stream cipher

Cryptanalysis and Brute-Force Attack

- Cryptanalysis
  - Attack relies on the nature of the algorithm plus some knowledge of the general characteristics of the plaintext
  - Attack exploits the characteristics of the algorithm to attempt to deduce a specific plaintext or to deduce the key being used
- Brute-force attack
  - Attacker tries every possible key on a piece of ciphertext until an intelligible translation into plaintext is obtained
  - On average, half of all possible keys must be tried to achieve success

Table 3.1 Types of Attacks on Encrypted Messages

Type of Attack	Known to Cryptanalyst
Ciphertext Only	• Encryption algorithm • Ciphertext
Known Plaintext	• Encryption algorithm • Ciphertext • One or more plaintext–ciphertext pairs formed with the secret key
Chosen Plaintext	• Encryption algorithm • Ciphertext • Plaintext message chosen by cryptanalyst, together with its corresponding ciphertext generated with the secret key
Chosen Ciphertext	• Encryption algorithm • Ciphertext • Ciphertext chosen by cryptanalyst, together with its corresponding decrypted plaintext generated with the secret key
Chosen Text	• Encryption algorithm • Ciphertext • Plaintext message chosen by cryptanalyst, together with its corresponding ciphertext generated with the secret key • Ciphertext chosen by cryptanalyst, together with its corresponding decrypted plaintext generated with the secret key

Encryption Scheme Security

- Unconditionally secure
  - No matter how much time an opponent has, it is impossible for him or her to decrypt the ciphertext simply because the required information is not there
- Computationally secure
  - The cost of breaking the cipher exceeds the value of the encrypted information
  - The time required to break the cipher exceeds the useful lifetime of the information

Pearson

Brute-Force Attack

- Involves trying every possible key until an intelligible translation of the ciphertext into plaintext is obtained
- On average, half of all possible keys must be tried to achieve success
- To supplement the brute-force approach, some degree of knowledge about the expected plaintext is needed, and some means of automatically distinguishing plaintext from garble is also needed

Strong Encryption

- The term *strong encryption* refers to encryption schemes that make it impractically difficult for unauthorized persons or systems to gain access to plaintext that has been encrypted
- Properties that make an encryption algorithm strong are:
  - Appropriate choice of cryptographic algorithm
  - Use of sufficiently long key lengths
  - Appropriate choice of protocols
  - A well-engineered implementation
  - Absence of deliberately introduced hidden flaws

Substitution Technique

- Is one in which the letters of plaintext are replaced by other letters or by numbers or symbols
- If the plaintext is viewed as a sequence of bits, then substitution involves replacing plaintext bit patterns with ciphertext bit patterns

Caesar Cipher

- Simplest and earliest known use of a substitution cipher
- Used by Julius Caesar
- Involves replacing each letter of the alphabet with the letter standing three places further down the alphabet
- Alphabet is wrapped around so that the letter following Z is A

plain:	meet	me	after	the	toga	party
cipher:	PHHW	PH	DIWHU	WKH	WRJD	SDUWB

Caesar Cipher Algorithm

- Can define transformation as:

  a b c d e f g h i j k l m n o p q r s t u v w x y z

  D E F G H I J K L M N O P Q R S T U V W X Y Z A B C

- Mathematically give each letter a number

  a b c d e f g h i j k l m n o p q r s t u v w x y z

  0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25

- Algorithm can be expressed as:

$$c = E(3, p) = (p + 3) \bmod (26)$$

- A shift may be of any amount, so that the general Caesar algorithm is:

$$C = E(k, p) = (p + k) \bmod 26$$

- Where k takes on a value in the range 1 to 25; the decryption algorithm is simply:

$$p = D(k, C) = (C - k) \bmod 26$$

Figure 3.3 Brute-Force Cryptanalysis of Caesar Cipher

KEY	PHHW PH DIWHU WKH WRJD SDUWB
1	oggv og chvgt vjg vqic rctva
2	nffu nf bgufs uif uphb qbsuz
3	meet me after the toga party
4	ldds ld zesdq sgd snfz ozqsx
5	kccr kc ydrcp rfc rmey nyprw
6	jbbq jb xcqbo qeb qldx mxoqv
7	iaap ia wbpan pda pkcw lwnpu
8	hzzo hz vaozm ocz ojbv kvmot
9	gyyn gy uznyl nby niau julns
10	fxxm fx tymxk max mhzt itkmr
11	ewwl ew sxlwj lzw lgys hsjlq
12	dvvk dv rwkvi kyv kfxr grikp
13	cuuj cu qvjuh jxu jewq fqhjo
14	btti bt puitg iwt idvp epgin
15	assh as othsf hvs hcuo dofhm
16	zrrg zr nsgre gur gbtn cnegl
17	yqqf yq mrfqd ftq fasm bmdfk
18	xppe xp lqepc esp ezrl alcej
19	wood wo kpdob dro dyqk zkbdi
20	vnnc vn jocna cqn cxpj yjach
21	ummb um inbmz bpm bwoi xizbg
22	tlla tl hmaly aol avnh whyaf
23	skkz sk glzkx znk zumg vgxze
24	rjjy rj fkyjw ymj ytlf ufwyd
25	qiix qi ejxiv xli xske tevxc

Sample of Compressed Text

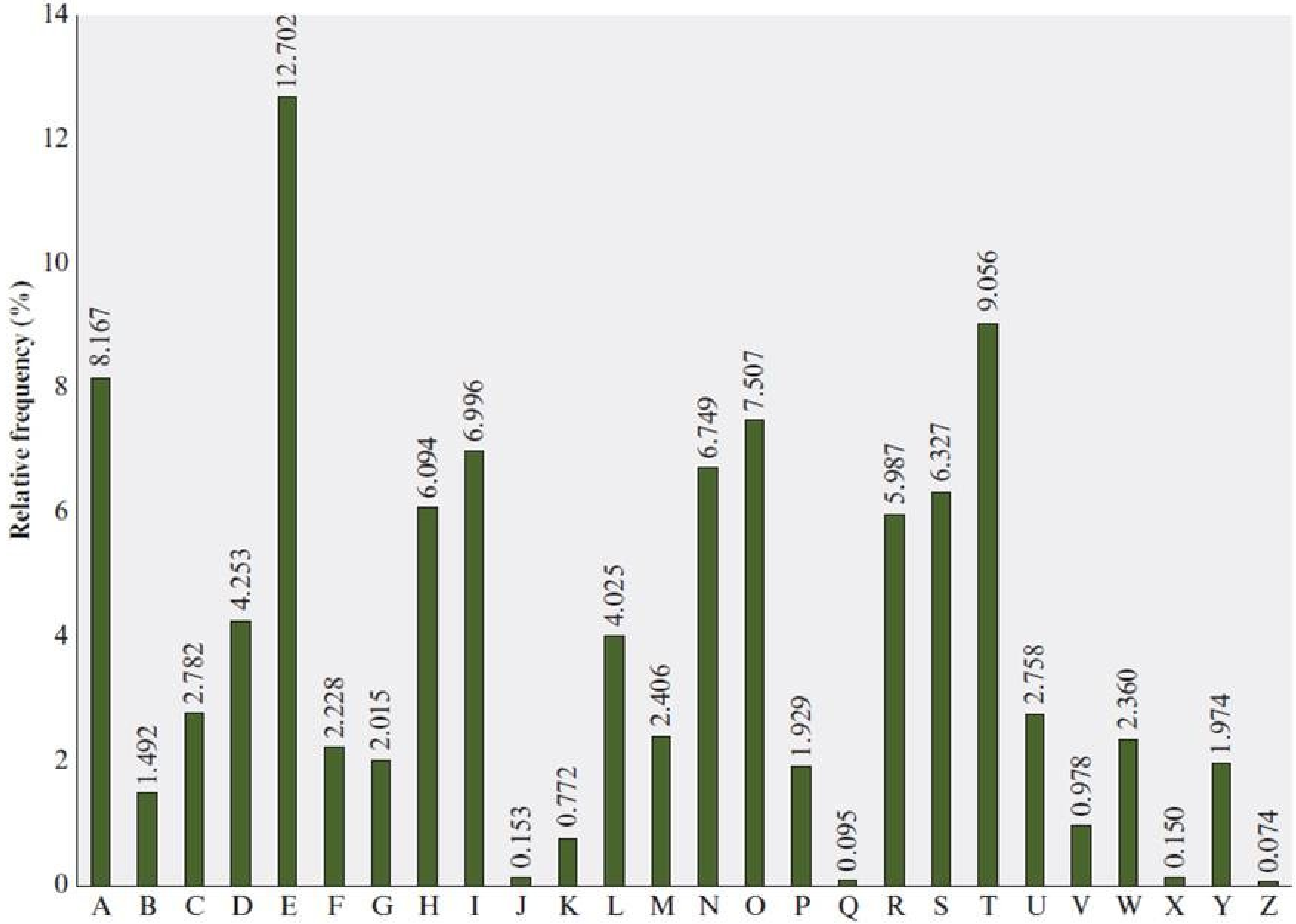
Figure 3.4 Sample of Compressed Text

```
~+Wµ"– Ω–O)≤4{∞‡¸ ë~Ω%ràu·¯í ◊¯Z-
Ú≠2Ò#Åæ∂ œ«q7¸Ωn·®3N◊Ú Œz'Y–ƒ∞Í[±Û_ èΩ,<NO¬±«ˇxã  Åä£èü3Å
x}ö§kºÂ
_yÍ ^ΔÉ] ˛¤ J/˚iTê&ı 'c<uΩ-
 ÄD(G WÄC~y_ïõÄW PÔı«ÎÜ†ç],¤¡ˇÌ^üÑπˇ≈ˇLˇ9OgflOˇ&Œ≤ ¬≤ ØÔ§˝:
 ˇŒ!SGqèvo^ ú\¸S>h<-*6ø‡%x´˝|fiÓ#≈˜my‰ˇ≥ñP<,ƒi Áj  Å◊¿˝Zù-
Ω¨Õ¯6Œÿ{% „ΩÊó ¸ï π÷ÁÎ˚úO2çSÿ´O-
2Äflßi /@^"∏KºªPŒπ¸úé^´3∑ˇöˇÔZÌ"Y¬ŸΩœY> Ω+eô/˙<K£¿*÷˜"≤û˜
B ZøK˜Qßÿüƒ˛!ÒflÎzsS/]>ÈQ ü
```

Monoalphabetic Cipher

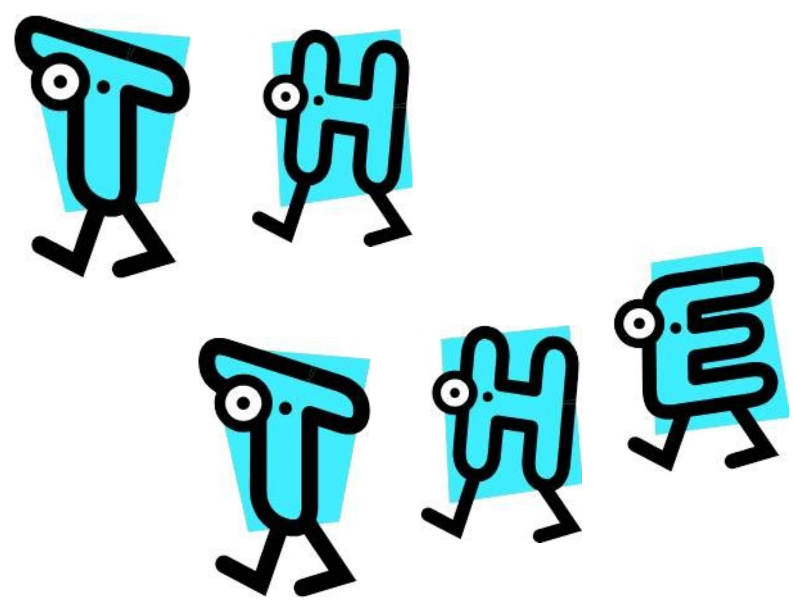
- Permutation
  - Of a finite set of elements *S* is an ordered sequence of all the elements of *S*, with each element appearing exactly once
- If the “cipher” line can be any permutation of the 26 alphabetic characters, then there are 26! or greater than 4 x 10^{26} possible keys
  - This is 10 orders of magnitude greater than the key space for DES
  - Approach is referred to as a *monoalphabetic substitution* cipher because a single cipher alphabet is used per message

Figure 3.5 Relative Frequency of Letters in English Text



Monoalphabetic Ciphers

- Easy to break because they reflect the frequency data of the original alphabet
- Countermeasure is to provide multiple substitutes (homophones) for a single letter
- Digram
  - Two-letter combination
  - Most common is *th*
- Trigram
  - Three-letter combination
  - Most frequent is *the*



Playfair Cipher

- Best-known multiple-letter encryption cipher
- Treats digrams in the plaintext as single units and translates these units into ciphertext digrams
- Based on the use of a 5 × 5 matrix of letters constructed using a keyword
- Invented by British scientist Sir Charles Wheatstone in 1854
- Used as the standard field system by the British Army in World War I and the U.S. Army and other Allied forces during World War II

Playfair Key Matrix

- Fill in letters of keyword (minus duplicates) from left to right and from top to bottom, then fill in the remainder of the matrix with the remaining letters in alphabetic order
- Using the keyword MONARCHY:

M	O	N	A	R
C	H	Y	B	D
E	F	G	I/J	K
L	P	Q	S	T
U	V	W	X	Z

3.2.2 Continued

Playfair Cipher

Figure 3.13 An example of a secret key in the Playfair cipher

Secret Key =

L	G	D	B	A
Q	M	H	E	C
U	R	N	I/J	F
X	V	S	O	K
Z	Y	W	T	P

To encrypt a message,

- break the message into digrams.
- If needed, append an uncommon monogram to complete the final digram.
- If both letters are the same, add an "X" after the first letter.
- Encrypt the new pair and continue.
- If the letters appear on the same row of your table, replace them with the letters to their immediate right respectively (wrapping around to the left side of the row if a letter in the original pair was on the right side of the row).
- If the letters appear on the same column of your table, replace them with the letters immediately below respectively.
- If the letters are not on the same row or column, replace them with the letters on the same row respectively but at the other pair of corners of the rectangle defined by the original pair. The order is important – the first letter of the encrypted pair is the one that lies on the same row as the first letter of the plaintext pair.

3.2.2 Continued

Playfair Cipher

Figure 3.13 An example of a secret key in the Playfair cipher

Secret Key =

L	G	D	B	A
Q	M	H	E	C
U	R	N	I/J	F
X	V	S	O	K
Z	Y	W	T	P

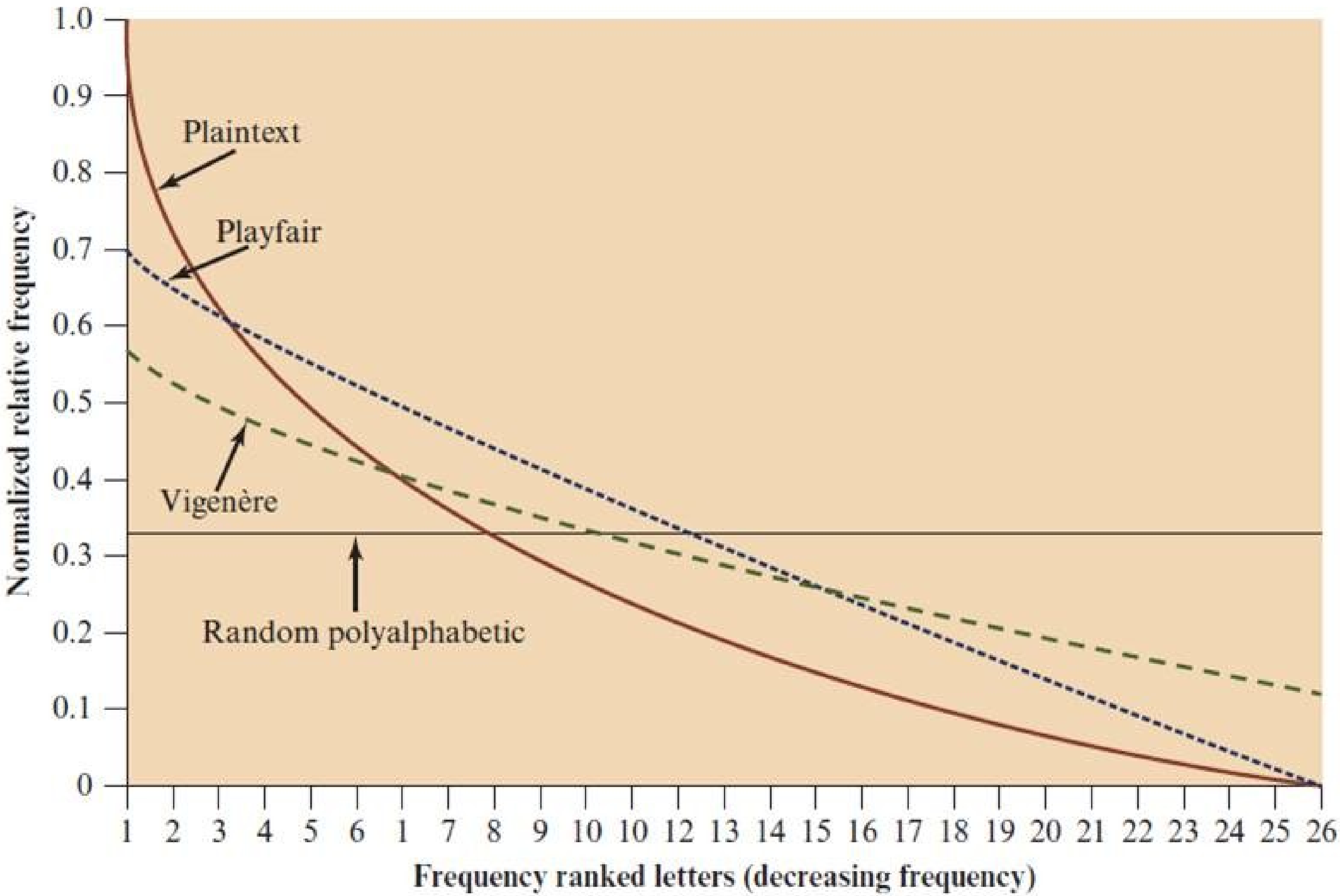
Example 3.15

Let us encrypt the plaintext “hello” using the key in Figure 3.13.

he → EC lx → QZ lo → BX

Plaintext: hello Ciphertext: ECQZBX

Figure 3.6 Relative Frequency of Occurrence of Letters



Hill Cipher

- Developed by the mathematician Lester Hill in 1929
- Strength is that it completely hides single-letter frequencies
  - The use of a larger matrix hides more frequency information
  - A 3 x 3 Hill cipher hides not only single-letter but also two-letter frequency information
- Strong against a ciphertext-only attack but easily broken with a known plaintext attack

3.2.2 Continued

Hill Cipher

Figure 3.15 Key in the Hill cipher

$$K = \begin{bmatrix} k_{11} & k_{12} & \ldots & k_{1m} \\ k_{21} & k_{22} & \ldots & k_{2m} \\ \vdots & \vdots & & \vdots \\ k_{m1} & k_{m2} & \ldots & k_{mm} \end{bmatrix}$$

$$C_1 = P_1 k_{11} + P_2 k_{21} + \cdots + P_m k_{m1}$$
$$C_2 = P_1 k_{12} + P_2 k_{22} + \cdots + P_m k_{m2}$$
$$\cdots$$
$$C_m = P_1 k_{1m} + P_2 k_{2m} + \cdots + P_m k_{mm}$$

Note

The key matrix in the Hill cipher needs to have a multiplicative inverse.

3.2.2 Continued

Example 3.20

For example, the plaintext "code is ready" can make a 3 × 4 matrix when adding extra bogus character "z" to the last block and removing the spaces. The ciphertext is "OHKNIHGKLISS".

Figure 3.16 Example 3.20

$$
\begin{array}{c} \mathrm{C} \\ \begin{bmatrix} 14 & 07 & 10 & 13 \\ 08 & 07 & 06 & 11 \\ 11 & 08 & 18 & 18 \end{bmatrix} \end{array}
=
\begin{array}{c} \mathrm{P} \\ \begin{bmatrix} 02 & 14 & 03 & 04 \\ 08 & 18 & 17 & 04 \\ 00 & 03 & 24 & 25 \end{bmatrix} \end{array}
\begin{array}{c} \mathrm{K} \\ \begin{bmatrix} 09 & 07 & 11 & 13 \\ 04 & 07 & 05 & 06 \\ 02 & 21 & 14 & 09 \\ 03 & 23 & 21 & 08 \end{bmatrix} \end{array}
$$

a. Encryption

$$
\begin{array}{c} \mathrm{P} \\ \begin{bmatrix} 02 & 14 & 03 & 04 \\ 08 & 18 & 17 & 04 \\ 00 & 03 & 24 & 25 \end{bmatrix} \end{array}
=
\begin{array}{c} \mathrm{C} \\ \begin{bmatrix} 14 & 07 & 10 & 13 \\ 08 & 07 & 06 & 11 \\ 11 & 08 & 18 & 18 \end{bmatrix} \end{array}
\begin{array}{c} \mathrm{K}^{-1} \\ \begin{bmatrix} 02 & 15 & 22 & 03 \\ 15 & 00 & 19 & 03 \\ 09 & 09 & 03 & 11 \\ 17 & 00 & 04 & 07 \end{bmatrix} \end{array}
$$

b. Decryption

3.2.2 Continued

Example 3.21

Assume that Eve knows that m = 3. She has intercepted three plaintext/ciphertext pair blocks (not necessarily from the same message) as shown in Figure 3.17.

Figure 3.17 Example 3.21

$$\begin{bmatrix} 05 & 07 & 10 \end{bmatrix} \longleftrightarrow \begin{bmatrix} 03 & 06 & 00 \end{bmatrix}$$

$$\begin{bmatrix} 13 & 17 & 07 \end{bmatrix} \longleftrightarrow \begin{bmatrix} 14 & 16 & 09 \end{bmatrix}$$

$$\begin{bmatrix} 00 & 05 & 04 \end{bmatrix} \longleftrightarrow \begin{bmatrix} 03 & 17 & 11 \end{bmatrix}$$

P C

3.2.2 Continued

Example 3.21 (Continued)

She makes matrices P and C from these pairs. Because P is invertible, she inverts the P matrix and multiplies it by C to get the K matrix as shown in Figure 3.18.

Figure 3.18 Example 3.21

$$\underset{K}{\begin{bmatrix} 02 & 03 & 07 \\ 05 & 07 & 09 \\ 01 & 02 & 11 \end{bmatrix}} = \underset{P^{-1}}{\begin{bmatrix} 21 & 14 & 01 \\ 00 & 08 & 25 \\ 13 & 03 & 08 \end{bmatrix}} \underset{C}{\begin{bmatrix} 03 & 06 & 00 \\ 14 & 16 & 09 \\ 03 & 17 & 11 \end{bmatrix}}$$

Now she has the key and can break any ciphertext encrypted with that key.

Polyalphabetic Ciphers

- Polyalphabetic substitution cipher
  - Improves on the simple monoalphabetic technique by using different monoalphabetic substitutions as one proceeds through the plaintext message
- All these techniques have the following features in common:
  - A set of related monoalphabetic substitution rules is used
  - A key determines which particular rule is chosen for a given transformation

Vigenère Cipher

- Best known and one of the simplest polyalphabetic substitution ciphers
- In this scheme the set of related monoalphabetic substitution rules consists of the 26 Caesar ciphers with shifts of 0 through 25
- Each cipher is denoted by a key letter which is the ciphertext letter that substitutes for the plaintext letter a

Example of Vigenère Cipher

- To encrypt a message, a key is needed that is as long as the message
- Usually, the key is a repeating keyword
- For example, if the keyword is *deceptive*, the message “we are discovered save yourself” is encrypted as:

key: deceptivedeceptivedeceptive

plaintext: wearediscoveredsaveyourself

ciphertext: ZICVTWQNGRZGVTWAVZHCQYGLMGJ

Vigenère Autokey System

- A keyword is concatenated with the plaintext itself to provide a running key
- Example:

key: deceptivewearediscoveredsav

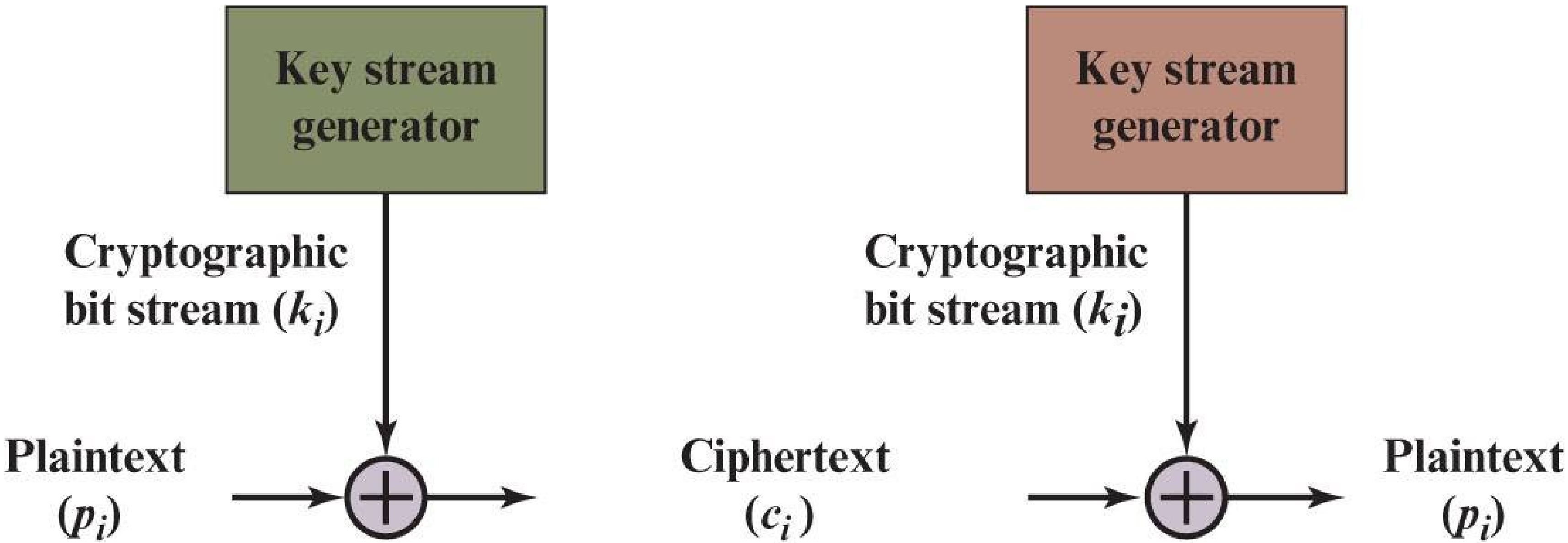
plaintext: wearediscoveredsaveyourself

ciphertext: ZICVTWQNGKZEIIGASXSTSLVVWLA

- Even this scheme is vulnerable to cryptanalysis
  - Because the key and the plaintext share the same frequency distribution of letters, a statistical technique can be applied

Vernam Cipher

Figure 3.7 Vernam Cipher



One-Time Pad

- Improvement to Vernam cipher proposed by an Army Signal Corp officer, Joseph Mauborgne
- Use a random key that is as long as the message so that the key need not be repeated
- Key is used to encrypt and decrypt a single message and then is discarded
- Each new message requires a new key of the same length as the new message
- Scheme is unbreakable
  - Produces random output that bears no statistical relationship to the plaintext
  - Because the ciphertext contains no information whatsoever about the plaintext, there is simply no way to break the code

Difficulties

- The one-time pad offers complete security but, in practice, has two fundamental difficulties:
  - There is the practical problem of making large quantities of random keys
    - Any heavily used system might require millions of random characters on a regular basis
  - Mammoth key distribution problem
    - For every message to be sent, a key of equal length is needed by both sender and receiver
- Because of these difficulties, the one-time pad is of limited utility
  - Useful primarily for low-bandwidth channels requiring very high security
- The one-time pad is the only cryptosystem that exhibits *perfect secrecy* (see Appendix F)

Rail Fence Cipher

- Simplest transposition cipher
- Plaintext is written down as a sequence of diagonals and then read off as a sequence of rows
- To encipher the message “meet me after the toga party” with a rail fence of depth 2, we would write:

m e m a t r h t g p r y

e t e f e t e o a a t

Encrypted message is:

MEMATRHTGPRYETEFETEOAAT

Row Transposition Cipher

- Is a more complex transposition
- Write the message in a rectangle, row by row, and read the message off, column by column, but permute the order of the columns
  - The order of the columns then becomes the key to the algorithm

Key: 4 3 1 2 5 6 7

Plaintext: a t t a c k p

o s t p o n e

d u n t i l t

w o a m x y z

Ciphertext: TTNAAPTMTSUOAODWCOIXKNLYPETZ

Pearson

Summary

- Present an overview of the main concepts of symmetric cryptography
- Explain the difference between cryptanalysis and brute-force attack
- Understand the operation of a monoalphabetic substitution cipher
- Understand the operation of a polyalphabetic cipher
- Present an overview of the Hill cipher

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