Information Security unit-I

INTRODUCTION: Computer data often travels from one computer to another, leaving the safety of its protected physical surroundings. Once the data is out of hand, people with bad intention could modify or forge your data, either for amusement or for their own benefit. Cryptography can reformat and transform our data, making it safer on its trip between computers. The technology is based on the essentials of secret codes, augmented by modern mathematics that protects our data in powerful ways.

• **Computer Security** - generic name for the collection of tools designed to protect data and to thwart hackers

• **Network Security** - measures to protect data during their transmission

• **Internet Security** - measures to protect data during their transmission over a collection of interconnected networks

THE OSI SECURITY ARCHITECTURE

To assess effectively the security needs of an organization and to evaluate and choose various security products and policies, the manager responsible for security needs some systematic way of defining the requirements for security and characterizing the approaches to satisfying those requirements. The OSI security architecture was developed in the context of the OSI protocol architecture, which is described in Appendix H. However, for our purposes in this chapter, an understanding of the OSI protocol architecture is not required. For our purposes, the OSI security architecture provides a useful, if abstract, overview of many of the concepts.. The OSI security architecture focuses on security attacks, mechanisms, and services. These can be defined briefly as follows:

Security Attacks, Services And Mechanisms To assess the security needs of an organization effectively, the manager responsible for security needs some systematic way of defining the requirements for security and characterization of approaches to satisfy those requirements. One approach is to consider three aspects of information security:

- **Security attack** – Any action that compromises the security of information owned by an organization.
- **Security mechanism** – A mechanism that is designed to detect, prevent or recover from a security attack.
- **Security service** – A service that enhances the security of the data processing systems and the information transfers of an organization. The services are intended to counter security attacks and they make use of one or more security mechanisms to provide the service.

Table 1.1. Threats and Attacks (RFC 2828)

Threat

A potential for violation of security, which exists when there is a circumstance, capability, action, or event that could breach security and cause harm. That is, a threat is a possible danger that might exploit a vulnerability.

Attack

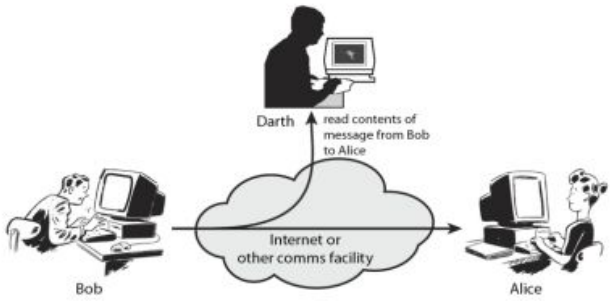
An assault on system security that derives from an intelligent threat; that is, an intelligent act that is a deliberate attempt (especially in the sense of a method or technique) to evade security services and violate the security policy of a system.

Security Attacks:

A useful means of classifying security attacks used both in X.800 and RFC 2828, is in terms of passive attacks and active attacks. It attempts to learn or make use of information from the system but does not affect system resources. An active attack attempts to alter system resources or affect their operation.

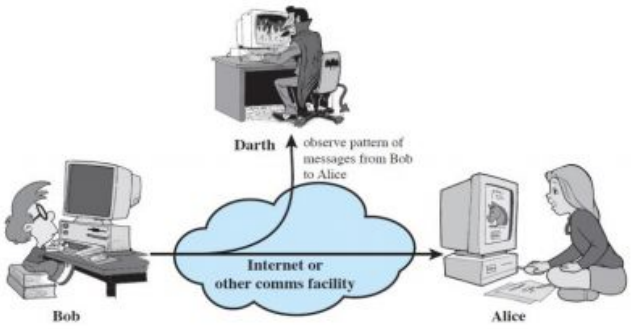
Passive Attacks:

Passive attacks are in the nature of eavesdropping on, or monitoring of, transmissions. The goal of the opponent is to obtain information that is being transmitted. Two types of passive attacks are the release of message contents and traffic analysis. The release of message contents is easily understood. A telephone conversation, an electronic mail message, and a transferred file may contain sensitive or confidential information. We would like to prevent an opponent from learning the contents of these transmissions.



Release of Message Contents

A second type of passive attack, traffic analysis, is subtler. Suppose that we had a way of masking the contents of messages or other information traffic so that opponents, even if they captured the message, could not extract the information from the message. The common technique for masking contents is encryption.



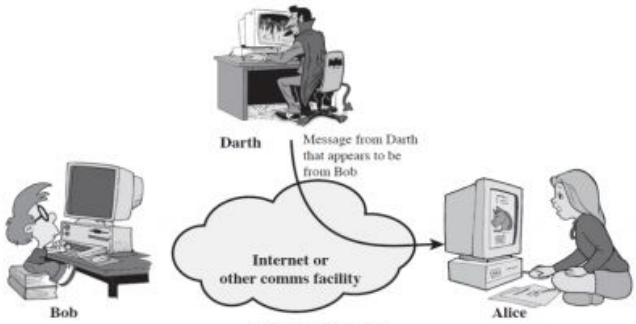
Traffic Analysis

Passive attacks are very difficult to detect, because they do not involve any alteration of the data. Typically, the message traffic is sent and received in an apparently normal fashion, and neither the sender nor receiver is aware that a third party has read the messages or observed the traffic pattern. However, it is feasible to prevent the success of these attacks, usually by means of encryption. Thus, the emphasis in dealing with passive attacks is on prevention rather than detection.

Active Attacks

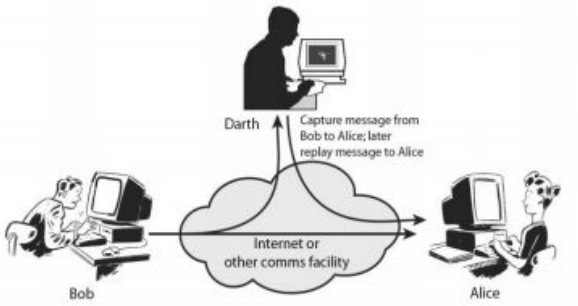
Active attacks involve some modification of the data stream or the creation of a false stream and can be subdivided into four categories: masquerade, replay, modification of messages, and denial of service.

A Masquerade takes place when one entity pretends to be a different entity. A masquerade attack usually includes one of the other forms of active attack.



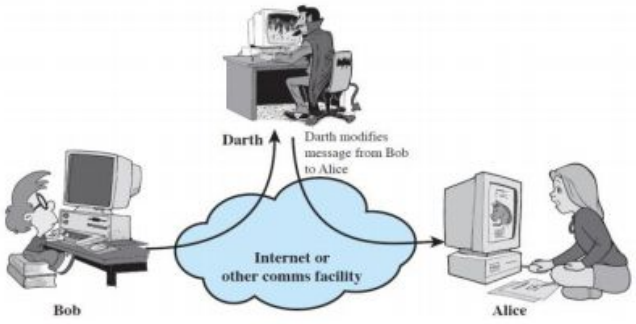
Masquerade

Replay involves the passive capture of a data unit and its subsequent retransmission to produce an unauthorized effect.



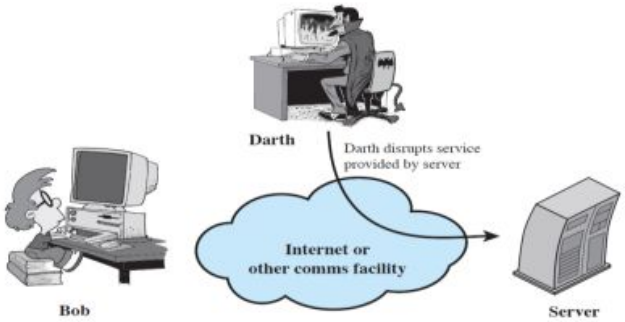
Replay

Modification of messages simply means that some portion of a legitimate message is altered, or that messages are delayed or reordered, to produce an unauthorized effect. For example, a message meaning "Allow John Smith to read confidential file accounts " is modified to mean "Allow Fred Brown to read confidential file accounts.



Modification of Messages

The denial of service prevents or inhibits the normal use or management of communications facilities. This attack may have a specific target; for example, an entity may suppress all messages directed to a particular destination (e.g., the security audit service). Another form of service denial is the disruption of an entire network, either by disabling the network or by overloading it with messages so as to degrade performance.



Denial of Service

SECURITY SERVICES:

A processing or communication service that is provided by a system to give a specific kind of protection to system resources; security services implement security policies and are implemented by security mechanisms.

X.800 divides these services into five categories and fourteen specific services

AUTHENTICATION	DATA INTEGRITY
The assurance that the communicating entity is the one that it claims to be. **Peer Entity Authentication** Used in association with a logical connection to provide confidence in the identity of the entities connected. **Data-Origin Authentication** In a connectionless transfer, provides assurance that the source of received data is as claimed. **ACCESS CONTROL** The prevention of unauthorized use of a resource (i.e., this service controls who can have access to a resource, under what conditions access can occur, and what those accessing the resource are allowed to do). **DATA CONFIDENTIALITY** The protection of data from unauthorized disclosure. **Connection Confidentiality** The protection of all user data on a connection. **Connectionless Confidentiality** The protection of all user data in a single data block	The assurance that data received are exactly as sent by an authorized entity (i.e., contain no modification, insertion, deletion, or replay). **Connection Integrity with Recovery** Provides for the integrity of all user data on a connection and detects any modification, insertion, deletion, or replay of any data within an entire data sequence, with recovery attempted. **Connection Integrity without Recovery** As above, but provides only detection without recovery. **Selective-Field Connection Integrity** Provides for the integrity of selected fields within the user data of a data block transferred over a connection and takes the form of determination of whether the selected fields have been modified, inserted, deleted, or replayed. **Connectionless Integrity** Provides for the integrity of a single connectionless data block and may take the form of detection of data modification. Additionally, a limited form of replay detection may be provided.

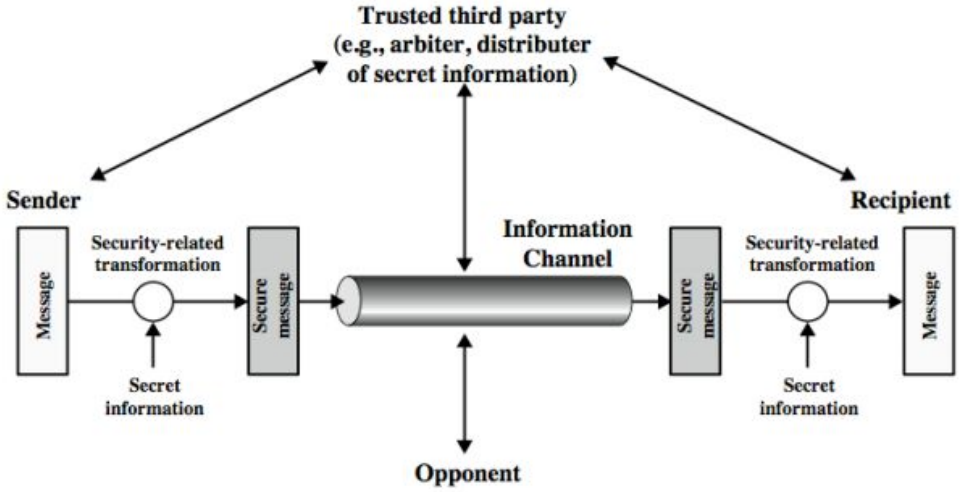
Selective-Field Confidentiality The confidentiality of selected fields within the user data on a connection or in a single data block. **Traffic-Flow Confidentiality** The protection of the information that might be derived from observation of traffic flows.	**Selective-Field Connectionless Integrity** Provides for the integrity of selected fields within a single connectionless data block; takes the form of determination of whether the selected fields have been modified. **NONREPUDIATION** Provides protection against denial by one of the entities involved in a communication of having participated in all or part of the communication. **Nonrepudiation, Origin** Proof that the message was sent by the specified party. **Nonrepudiation, Destination** Proof that the message was received by the specified party

Security Mechanisms:

The mechanisms are divided into those that are implemented in a specific protocol layer, such as TCP or an application-layer protocol, and those that are not specific to any particular protocol layer or security service.

SPECIFIC SECURITY MECHANISMS	PERVASIVE SECURITY MECHANISMS
May be incorporated into the appropriate protocol layer in order to provide some of the OSI security services.	Mechanisms that are not specific to any particular OSI security service or protocol layer.
Encipherment The use of mathematical algorithms to transform data into a form that is not readily intelligible. The transformation and subsequent recovery of the data depend on an algorithm and zero or more encryption keys.	**Trusted Functionality** That which is perceived to be correct with respect to some criteria (e.g., as established by a security policy).
Digital Signature Data appended to, or a cryptographic transformation of, a data unit that allows a recipient of the data unit to prove the source and integrity of the data unit and protect against forgery (e.g., by the recipient).	**Security Label** The marking bound to a resource (which may be a data unit) that names or designates the security attributes of that resource.
Access Control A variety of mechanisms that enforce access rights to resources.	**Event Detection** Detection of security-relevant events.
Data Integrity A variety of mechanisms used to assure the integrity of a data unit or stream of data units.	**Security Audit Trail** Data collected and potentially used to facilitate a security audit, which is an independent review and examination of system records and activities.
Authentication Exchange A mechanism intended to ensure the identity of an entity by means of information exchange.	**Security Recovery** Deals with requests from mechanisms, such as event handling and management functions, and takes recovery actions.
Traffic Padding The insertion of bits into gaps in a data stream to frustrate traffic analysis attempts.	
Routing Control Enables selection of particular physically secure routes for certain data and allows routing changes, especially when a breach of security is suspected.	
Notarization The use of a trusted third party to assure certain properties of a data exchange.	

A MODEL FOR NETWORK SECURITY



A message is to be transferred from one party to another across some sort of internet. The two parties, who are the principals in this transaction, must cooperate for the exchange to take place. A logical information channel is established by defining a route through the internet from source to destination and by the cooperative use of communication protocols (e.g., TCP/IP) by the two principals. **using this model requires us to:**

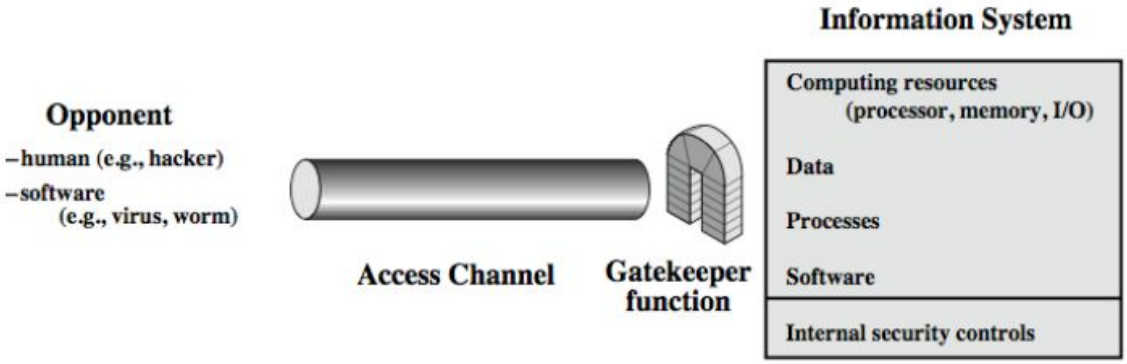
– design a suitable algorithm for the security transformation

– generate the secret information (keys) used by the algorithm

– develop methods to distribute and share the secret information

– specify a protocol enabling the principals to use the transformation and secret information for a security service

MODEL FOR NETWORK ACCESS SECURITY



- **using this model requires us to:**

  – select appropriate gatekeeper functions to identify users

  – implement security controls to ensure only authorized users access designated information or resources
- **trusted computer systems can be used to implement this model**

CONVENTIONAL ENCRYPTION

Symmetric encryption also referred to as conventional encryption or single-key encryption was the only type of encryption in use prior to the development of public key encryption in the 1970s.

Some basic terminologies used:

• **plaintext** - the original message

• **ciphertext** - the coded message

• **encipher (encrypt)** - converting plaintext to ciphertext

• **decipher (decrypt) -** restoring the plaintext from the ciphertext

• **cryptography** - study of encryption principles/methods

• **cryptanalysis (codebreaking)** - the study of principles/ methods of deciphering ciphertext *without* knowing key

• **cryptology** - the field of both cryptography and cryptanalysis

SYMMETRIC CIPHER MODEL

A symmetric encryption scheme has five ingredients:

• **Plaintext:** This is the original intelligible message or data that is fed into the algorithm as input.

• **Encryption algorithm:** The encryption algorithm performs various substitutions and transformations on the plaintext.

• **Secret key:** The secret key is also input to the encryption algorithm. The key is a value independent of the plaintext and of the algorithm. The algorithm will produce a different output depending on the specific key being used at the time. The exact substitutions and transformations performed by the algorithm depend on the key.

• **Ciphertext:** This is the scrambled message produced as output. It depends on the plaintext and the secret key. For a given message, two different keys will produce two different ciphertexts. The ciphertext is an apparently random stream of data and, as it stands, is unintelligible.

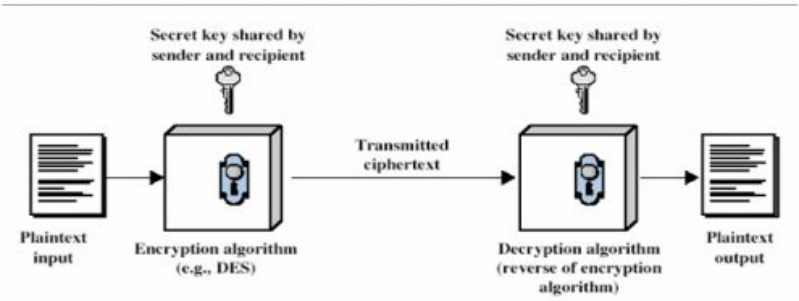
• **Decryption algorithm:** This is essentially the encryption algorithm run in reverse. It takes the ciphertext and the secret key and produces the original plaintext.

Two requirements for secure use of symmetric encryption:

– a strong encryption algorithm

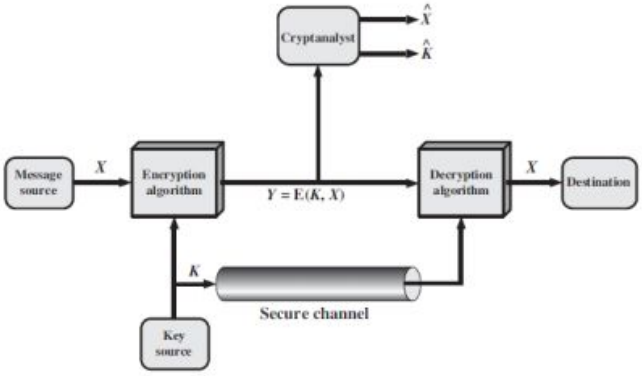
– Sender and receiver must have obtained copies of the secret key in a secure fashion and must keep the key secure.

If someone can discover the key and knows the algorithm, all communication using this key is readable.



We assume that it is impractical to decrypt a message on the basis of the ciphertext *plus* knowledge of the encryption/decryption algorithm. In other words, we do not need to keep the algorithm secret; we need to keep only the key secret. This feature of symmetric encryption is what makes it feasible for widespread use.

If the key is generated at the message source, then it must also be provided to the destination by means of some secure channel. Alternatively, a third party could generate the key and securely deliver it to both source and destination.



Cryptography:

Cryptographic systems are generally classified along 3 independent dimensions:

Type of operations used for transforming plain text to cipher text:
All the encryption algorithms are based on two general principles: **substitution**, in which each element in the plaintext is mapped into another element, and **transposition**, in which elements in the plaintext are rearranged.

The number of keys used:
If the sender and receiver uses same key then it is said to be **symmetric key (or) single key (or) conventional encryption**. If the sender and receiver use different keys then it is said to be **public key encryption**.

The way in which the plain text is processed:

A *block cipher* processes the input one block of elements at a time, producing an output block for each input block. A *stream cipher* processes the input elements continuously, producing output one element at a time, as it goes along.

Cryptanalysis:

The process of attempting to discover X or K or both is known as cryptanalysis. The strategy used by the cryptanalysis depends on the nature of the encryption scheme and the information available to the cryptanalyst.
There are various types of cryptanalytic attacks based on the amount of information known to the cryptanalyst.
Cipher text only – A copy of cipher text alone is known to the cryptanalyst.

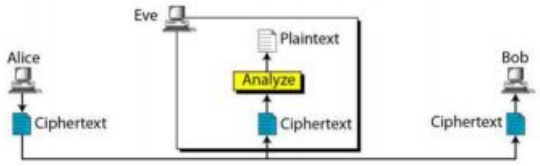
Known plaintext – The cryptanalyst has a copy of the cipher text and the corresponding plaintext.

Chosen plaintext – The cryptanalysts gains temporary access to the encryption machine. They cannot open it to find the key, however; they can encrypt a large number of suitably chosen plaintexts and try to use the resulting cipher texts to deduce the key.
Chosen cipher text – The cryptanalyst obtains temporary access to the decryption machine, uses it to decrypt several string of symbols, and tries to use the results to deduce the key.

Cryptanalysis
Cryptanalysis: Cryptanalytic attacks rely on the nature of the algorithm plus perhaps some knowledge of the general characteristics of the plaintext or even some sample plaintext–ciphertext pairs. This type of attack exploits the characteristics of the algorithm to attempt to deduce a specific plaintext or to deduce the key being used.

Brute-force attack: The 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.
Types of Attacks on Encrypted Messages
Ciphertext-only attack:
In a **ciphertext-only attack**, Eve has access to only some ciphertext. She tries to find the corresponding key and the plaintext. The ciphertext-only attack is the most probable one because Eve needs only the ciphertext for this attack.

Figure 3.4 Ciphertext-only attack

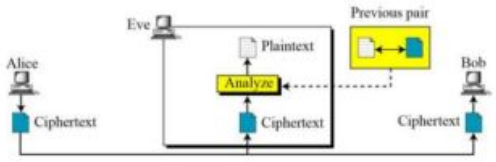


Known-Plaintext Attack:
In a **known-plaintext attack,** Eve has access to some plaintext/ciphertext pairs in addition to the intercepted ciphertext that she wants to break.

The plaintext/ciphertext pairs have been collected earlier. For example, Alice has sent a secret message to Bob, but she has later made the contents of the message public.

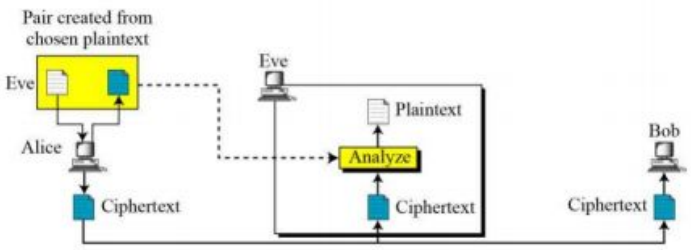
This attack is easier to implement because Eve has more information to use for analysis. However, it is less likely to happen because Alice may have changed her key or may have not disclosed the content of any previous messages.

Figure 3.5 Known-plaintext attack



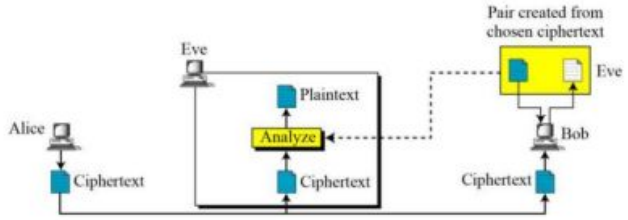
Chosen-Plaintext Attack:

The **chosen-plaintext attack** is similar to the known-plaintext attack, but the plaintext/ciphertext pairs have been chosen by the attacker herself. This can happen, for example, if Eve has access to Alice's computer. She can choose some plaintext and intercept the created ciphertext. This type of attack is much easier to implement, but it is much less likely to happen



Chosen-ciphertext Attack:

The **chosen-ciphertext attack** is similar to the chosen-plaintext attack, except that Eve chooses some ciphertext and decrypts it to form a ciphertext/plaintext pair. This can happen if Eve has access to Bob's computer



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

CLASSICAL ENCRYPTION TECHNIQUES

There are two basic building blocks of all encryption techniques: substitution and transposition.

I. SUBSTITUTION TECHNIQUES A 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 cipher text bit patterns.

(i)**Caesar cipher (or) shift cipher** The earliest known use of a substitution cipher and the simplest was by Julius Caesar. The Caesar cipher involves replacing each letter of the alphabet with the letter standing 3 places further down the alphabet.

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

Note that the alphabet is wrapped around, so that the letter following Z is A. We can define the transformation by listing all possibilities, as follows:

```
Plain : 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
cipher: 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
```

Let us assign a numerical equivalent to each letter:

When letters are involved, the following conventions are used in this book. Plaintext is always in lowercase; ciphertext is in uppercase; key values are in italicized lowercase.

a	b	c	d	e	f	g	h	i	j	k	l	m
0	1	2	3	4	5	6	7	8	9	10	11	12

n	o	p	q	r	s	t	u	v	w	x	y	z
13	14	15	16	17	18	19	20	21	22	23	24	25

Then the algorithm can be expressed as follows. For each plaintext letter p, substitute the ciphertext letter C:

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

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

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

where takes on a value in the range 1 to 25.The decryption algorithm is simply

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

Three important characteristics of this problem enabled us to use a bruteforce cryptanalysis:

1. The encryption and decryption algorithms are known.

2. There are only 25 keys to try.

3. The language of the plaintext is known and easily recognizable.

Monoalphabetic Ciphers:

With only 25 possible keys, the Caesar cipher is far from secure. Hence, another approach referred to as monoalphabetic substitution cipher is introduced, in which instead of taking any permutation(possibility) of 26 characters then there are 26! or greater than possible keys.

Monoalphabetic cipher can use a key in different order. For example

Using the key "zebras" the ciphertext will be as follows.

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
Z	E	B	R	A	S	C	D	F	G	H	I	J	K	L	M

Q	R	S	T	U	V	W	X	Y	Z
N	O	P	Q	T	U	V	W	X	Y

PlainText : hello

CipherText :DAIIL

The cryptanalyst may try to break the ciphertext by looking at the ciphertext and identifying the frequency of letters in the text, comparing it with the relative frequency of the letters in English Text, and the looking at the frequency of two-letter word(digram), three letter words(trigram) and so on.

Monoalphabetic ciphers are easy to break because they reflect the frequency data of the original alphabet.

A countermeasure is to provide multiple substitutes, known as homophones, for a single letter.

Playfair cipher:

The best known multiple letter encryption cipher is the playfair, which treats digrams in the plaintext as single units and translates these units into cipher text digrams.

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

The playfair algorithm is based on the use of 5x5 matrix of letters constructed using a keyword. Let the keyword be „monarchy". The matrix is constructed by filling in the letters of the keyword (minus duplicates) from left to right and from top to bottom, and then filling in the remainder of the matrix with the remaining letters in alphabetical order.

The letter „i" and „j" count as one letter. Plaintext is encrypted two letters at a time according to the following rules:

- Repeating plaintext letters that would fall in the same pair are separated with a filler letter such as „x". so that balloon would be treated as ba lx lo on.
- Two Plaintext letters that fall in the same row of the matrix are each replaced by the letter to the right, with the first element of the row circularly following the last. For example, ar is encrypted as RM.
- Two Plaintext letters that fall in the same column are replaced by the letter beneath, with the top element of the column circularly following the last. For example, mu is encrypted as CM.
- Otherwise, each plaintext letter in a pair is replaced by the letter that lies in its own row and the column occupied by the other plaintext letter. Thus, hs becomes BP and ea becomes IM (or JM, as the encipherer wishes).

Plaintext = meet me at the school house
Splitting two letters as a unit => me et me at th es ch ox ol ho us ex
Corresponding cipher text => CL KL CL RS PD IL HY AV MP HF XL IU

Strength of playfair cipher

- Playfair cipher is a great advance over simple mono alphabetic ciphers.
- Since there are 26 letters, 26x26 = 676 digrams are possible, so identification of individual digram is more difficult.

- Frequency analysis is much more difficult.

Hill Cipher:

The Hill Cipher was invented by Lester S. Hill in 1929, and like the other Digraphic Ciphers it acts on groups of letters. Unlike the others though it is extendable to work on different sized blocks of letters. So, technically it is a polygraphic substitution cipher, as it can work on digraphs, trigraphs (3 letter blocks) or theoretically any sized blocks.

The Hill Cipher uses an area of mathematics called Linear Algebra, and in particular requires the user to have an elementary understanding of matrices. It also makes use of Modulo Arithmetic (like the Affine Cipher). Because of this, the cipher has a significantly more mathematical nature than some of the others. However, it is this nature that allows it to act (relatively) easily on larger blocks of letters.

Encryption

To encrypt a message using the Hill Cipher we must first turn our keyword into a key matrix (a 2 x 2 matrix for working with digraphs, a 3 x 3 matrix for working with trigraphs, etc). We also turn the plaintext into digraphs (or trigraphs) and each of these into a column vector. We then perform matrix multiplication modulo the length of the alphabet (i.e. 26) on each vector. These vectors are then converted back into letters to produce the ciphertext.

2x2Example

We shall encrypt the plaintext message "short example" using the keyword *hill* and a 2 x 2 matrix. The first step is to turn the keyword into a matrix. If the keyword was longer than the 4 letters needed, we would only take the first 4 letters, and if it was shorter, we would fill it up with the alphabet in order (much like a Mixed Alphabet).

$$\begin{pmatrix} H & I \\ L & L \end{pmatrix}$$

The keyword written as a matrix.

With the keyword in a matrix, we need to convert this into a key matrix. We do this by converting each letter into a number by its position in the alphabet (starting at 0). So, A = 0, B = 1, C= 2, D = 3, etc.

$$\begin{pmatrix} 7 & 8 \\ 11 & 11 \end{pmatrix}$$

The key matrix (each letter of the keyword is converted to a number).

We now split the plaintext into digraphs, and write these as column vectors. That is, in the first column vector we write the first plaintext letter at the top, and the second letter at the bottom. Then we move to the next column vector, where the third plaintext letter goes at the top, and the fourth at the bottom. This continues for the whole plaintext.

$$\begin{pmatrix} s \\ h \end{pmatrix} \begin{pmatrix} o \\ r \end{pmatrix} \begin{pmatrix} t \\ e \end{pmatrix} \begin{pmatrix} x \\ a \end{pmatrix} \begin{pmatrix} m \\ p \end{pmatrix} \begin{pmatrix} l \\ e \end{pmatrix}$$

The plaintext "short example" split into column vectors.

Now we must convert the plaintext column vectors in the same way that we converted the keyword into the key matrix. Each letter is replaced by its appropriate number.

$$\begin{pmatrix}18\\7\end{pmatrix}\begin{pmatrix}14\\17\end{pmatrix}\begin{pmatrix}19\\4\end{pmatrix}\begin{pmatrix}23\\0\end{pmatrix}\begin{pmatrix}12\\15\end{pmatrix}\begin{pmatrix}11\\4\end{pmatrix}$$

The plaintext converted into numeric column vectors.

Now we must perform some matrix multiplication. We multiply the key matrix by each column vector in turn. We shall go through the first of these in detail, then the rest shall be presented in less detail. We write the key matrix first, followed by the column vector.

$$\begin{pmatrix}7 & 8\\11 & 11\end{pmatrix}\begin{pmatrix}18\\7\end{pmatrix}$$

To perform matrix multiplication we "combine" the top row of the key matrix with the column vector to get the top element of the resulting column vector. We then "combine" the bottom row of the key matrix with the column vector to get the bottom element of the resulting column vector. The way we "combine" the four numbers to get a single number is that we multiply the first element of the key matrix row by the top element of the column vector, and multiply the second element of the key matrix row by the bottom element of the column vector. We then add together these two answers.

$$\begin{pmatrix}a & b\\c & d\end{pmatrix}\begin{pmatrix}x\\y\end{pmatrix}=\begin{pmatrix}ax+by\\cx+dy\end{pmatrix}$$

That is, we follow the rules given by the algebraic method shown to the left.

The algebraic rules of matrix multiplication.

In our case we perform the two calculations on the right. We then right these two answers out in a column vector as shown below.

$$7\times 18+8\times 7=182$$

$$11\times 18+11\times 7=275$$

The calculations performed when doing a matrix multiplication.

$$\begin{pmatrix}7 & 8\\11 & 11\end{pmatrix}\begin{pmatrix}18\\7\end{pmatrix}=\begin{pmatrix}182\\275\end{pmatrix}$$

The shorthand for the matrix multiplication.

Next we have to take each of these numbers, in our resultant column vector, modulo 26 (remember that means divide by 26 and take the remainder).

$$\begin{pmatrix}7 & 8\\11 & 11\end{pmatrix}\begin{pmatrix}18\\7\end{pmatrix}=\begin{pmatrix}182\\275\end{pmatrix}=\begin{pmatrix}0\\15\end{pmatrix}\ mod\ 26$$

Reducing the resultant column vector modulo 26.

Finally we have to convert these numbers back to letters, so 0 becomes "A" and 15 becomes "P", and our first two letters of the ciphertext are "AP".

$$\begin{pmatrix} H & I \\ L & L \end{pmatrix}\begin{pmatrix} S \\ h \end{pmatrix} = \begin{pmatrix} 7 & 8 \\ 11 & 11 \end{pmatrix}\begin{pmatrix} 18 \\ 7 \end{pmatrix} = \begin{pmatrix} 182 \\ 275 \end{pmatrix} = \begin{pmatrix} 0 \\ 15 \end{pmatrix} \ mod\ 26 = \begin{pmatrix} A \\ P \end{pmatrix}$$

The whole calculation: converting to numbers; the matrix multiplication; reducing modulo 26; converting back to letters.

$$\begin{pmatrix} 7 & 8 \\ 11 & 11 \end{pmatrix}\begin{pmatrix} 18 \\ 7 \end{pmatrix}$$

$$7 \times 18 + 8 \times 7 = 182$$

$$11 \times 18 + 11 \times 7 = 275$$

$$\begin{pmatrix} 7 & 8 \\ 11 & 11 \end{pmatrix}\begin{pmatrix} 18 \\ 7 \end{pmatrix} = \begin{pmatrix} 182 \\ 275 \end{pmatrix}$$

$$\begin{pmatrix} 7 & 8 \\ 11 & 11 \end{pmatrix}\begin{pmatrix} 18 \\ 7 \end{pmatrix} = \begin{pmatrix} 182 \\ 275 \end{pmatrix} = \begin{pmatrix} 0 \\ 15 \end{pmatrix} \ mod\ 26$$

$$\begin{pmatrix} H & I \\ L & L \end{pmatrix}\begin{pmatrix} S \\ h \end{pmatrix} = \begin{pmatrix} 7 & 8 \\ 11 & 11 \end{pmatrix}\begin{pmatrix} 18 \\ 7 \end{pmatrix} = \begin{pmatrix} 182 \\ 275 \end{pmatrix} = \begin{pmatrix} 0 \\ 15 \end{pmatrix} \ mod\ 26 = \begin{pmatrix} A \\ P \end{pmatrix}$$

This gives us a final ciphertext of "APADJ TFTWLFJ".

Decryption process:

To decrypt a ciphertext encoded using the Hill Cipher, we must find the inverse matrix. Once we have the inverse matrix, the process is the same as encrypting. That is we multiply the inverse key matrix by the column vectors that the ciphertext is split into, take the results modulo the length of the alphabet, and finally convert the numbers back to letters.

Since the majority of the process is the same as encryption, we are going ot focus on finding the inverse key matrix (not an easy task), and will then skim quickly through the other steps (for more information see Encryption above).

In general, to find the inverse of the key matrix, we perform the calculation below, where K is the key matrix, d is the determinant of the key matrix and $adj(K)$ is the adjugate matrix of K.

$$K^{-1} = d^{-1} \times adj(K)$$

General method to calculate the inverse key matrix.

$$\begin{pmatrix} H & I \\ L & L \end{pmatrix}$$

The keyword written as a matrix.

2 x 2 Example

We shall decrypt the example above, so we are using the keyword *hill* and our ciphertext is "APADJ TFTWLFJ". We start by writing out the keyword as a matrix and converting this into a key matrix as for encryption. Now we must convert this to the inverse key matrix, for which there are several steps.

$$\begin{pmatrix} 7 & 8 \\ 11 & 11 \end{pmatrix}$$

The key matrix (each letter of the keyword is converted to a number).

Step 1 - Find the Multiplicative Inverse of the Determinant

The determinant is a number that relates directly to the entries of the matrix. It is found by multiplying the top left number by the bottom right number and subtracting from this the product of the top right number and the bottom left number. This is shown algebraically below. Note that the notation for determinant has straight lines instead of brackets around our matrix.

$$\begin{vmatrix} a & b \\ c & d \end{vmatrix} = ad - bc$$

Algebraic method to calculate the determinant of a 2 x 2 matrix.

Once we have found this value, we need to take the number modulo 26. Below is the way to calculate the determinant for our example.

$$\begin{vmatrix} 7 & 8 \\ 11 & 11 \end{vmatrix} = 7 \times 11 - 8 \times 11 = -11 = 15 \ mod \ 26$$

Calculating the determinant of our 2 x 2 key matrix.

We now have to find the multiplicative inverse of the determinant working modulo 26. That is, the number between 1 and 25 that gives an answer of 1 when we multiply it by the determinant. So, in this case, we are looking for the number that we need to multiply 15 by to get an answer of 1 modulo 26. There are algorithms to calculate this, but it is often easiest to use trial and error to find the inverse.

$$dd^{-1} = 1 \ mod \ 26$$

If d is the determinant, then we are looking for the inverse of d.

$$15 \times x = 1 \ mod \ 26$$

The multiplicative inverse is the number we multiply 15 by to get 1 modulo 26.

$$15 \times 7 = 105 = 1 \, mod \, 26$$

This calculation gives us an answer of 1 modulo 26.

So the multiplicative inverse of the determinant modulo 26 is 7. We shall need this number later.

Step 2 - Find the Adjugate Matrix

The adjugate matrix is a matrix of the same size as the original. For a 2 x 2 matrix, this is fairly straightforward as it is just moving the elements to different positions and changing a couple of signs. That is, we swap the top left and bottom right numbers in the key matrix, and change the sign of the the top right and bottom left numbers. Algebraically this is given below.

$$adj \begin{pmatrix} a & b \\ c & d \end{pmatrix} = \begin{pmatrix} d & -b \\ -c & a \end{pmatrix}$$

The adjugate matrix of a 2 x 2 matrix.

Again, once we have these values we will need to take each of them modulo 26 (in particular, we need to add 26 to the negative values to get a number between 0 and 25. For our example we get the matrix below.

$$adj \begin{pmatrix} 7 & 8 \\ 11 & 11 \end{pmatrix} = \begin{pmatrix} 11 & -8 \\ -11 & 7 \end{pmatrix} = \begin{pmatrix} 11 & 18 \\ 15 & 7 \end{pmatrix}$$

The adjugate matrix of the key matrix.

Step 3 - Multiply the Multiplicative Inverse of the Determinant by the Adjugate Matrix
To get the inverse key matrix, we now multiply the inverse determinant (that was 7 in our case) from step 1 by each of the elements of the adjugate matrix from step 2. Then we take each of these answers modulo 26.

$$7 \times \begin{pmatrix} 11 & 18 \\ 15 & 7 \end{pmatrix} = \begin{pmatrix} 77 & 126 \\ 165 & 49 \end{pmatrix} = \begin{pmatrix} 25 & 22 \\ 1 & 23 \end{pmatrix} \, mod \, 26$$

Multiplying the multiplicative inverse of the determinant by the adjugate to get the inverse key matrix.

That is:

$$if\ K = \begin{pmatrix} 7 & 8 \\ 11 & 11 \end{pmatrix}, then\ K^{-1} = \begin{pmatrix} 25 & 22 \\ 1 & 23 \end{pmatrix}$$

Now we have the inverse key matrix, we have to convert the ciphertext into column vectors and multiply the inverse matrix by each column vector in turn, take the results modulo 26 and convert these back into letters to get the plaintext.

$$\begin{pmatrix} 25 & 22 \\ 1 & 23 \end{pmatrix}\begin{pmatrix} A \\ P \end{pmatrix} = \begin{pmatrix} 25 & 22 \\ 1 & 23 \end{pmatrix}\begin{pmatrix} 0 \\ 15 \end{pmatrix}$$
$$= \begin{pmatrix} 25 \times 0 + 22 \times 15 \\ 1 \times 0 + 23 \times 15 \end{pmatrix}$$
$$= \begin{pmatrix} 330 \\ 345 \end{pmatrix}$$
$$= \begin{pmatrix} 18 \\ 7 \end{pmatrix}\ mod\ 26$$
$$= \begin{pmatrix} S \\ h \end{pmatrix}$$

The decryption of the first digraph.

We get back our plaintext of "short example".

Polyalphabetic Ciphers:

Another way to improve on the simple monoalphabetic technique is to use different monoalphabetic substitutions as one proceeds through the plaintext message. The general name for this approach is **polyalphabetic substitution cipher**.

All these techniques have the following features in common:

1. A set of related monoalphabetic substitution rules is used.

2. A key determines which particular rule is chosen for a given transformation.

VIGEN`ERE CIPHER The best known, and one of the simplest, polyalphabetic ciphers is the Vigenère cipher. 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.

We can express the Vigenère cipher in the following manner. Assume a sequence of plaintext letters P = p0, p1, p2, …. , pn-1 and a key consisting of the sequence of letters K = k0, k1, k2,…, km-1 , where typically m<n .The sequence of ciphertext letters C = C0, C1, C2, Á , Cn-1is calculated as follows:

C = C0, C1, C2, Á , Cn-1 = E(K, P) = E[(k0, k1, k2, .., km-1), (p0, p1, p2, …., pn-1)]
= (p0 + k0) mod 26, (p1 + k1) mod 26, … , (pm-1 + km-1) mod 26,
(pm + k0) mod 26, (pm+1 + k1) mod 26,… , (p2m-1 + km-1) mod 26, …

Thus, the first letter of the key is added to the first letter of the plaintext, mod 26, the second letters are added, and so on through the first m letters of the plaintext. For the next m letters of the plaintext, the key letters are repeated. This process continues until all of the plaintext sequence is encrypted. A general equation of the encryption process is

$$Ci = (pi + k) \bmod 26$$

Similarly, decryption is a generalization of

$$pi = (Ci - k) \bmod 26$$

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
```

Expressed numerically, we have the following result.

key	3	4	2	4	15	19	8	21	4	3	4	2	4	15
plaintext	22	4	0	17	4	3	8	18	2	14	21	4	17	4
ciphertext	25	8	2	21	19	22	16	13	6	17	25	6	21	19

key	19	8	21	4	3	4	2	4	15	19	8	21	4
plaintext	3	18	0	21	4	24	14	20	17	18	4	11	5
ciphertext	22	0	21	25	7	2	16	24	6	11	12	6	9

The strength of this cipher is that there are multiple ciphertext letters for each plaintext letter, one for each unique letter of the keyword. Thus, the letter frequency information is obscured. However, not all knowledge of the plaintext structure is lost.

Autokey System:
Vigenère proposed what is referred to as an autokey system, in which a keyword is concatenated with the plaintext itself to provide a running key. For our 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 The ultimate defense against such a cryptanalysis is to choose a keyword that is as long as the plaintext and has no statistical relationship to it. Such a system was introduced by an AT&T engineer named Gilbert Vernam in 1918. His system works on binary data (bits) rather than letters.The system can be expressed succinctly as follows

$$ci = pi \oplus ki$$

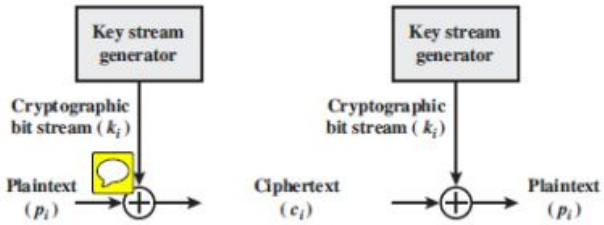
where

p_i=ith binary digit of plaintext

k_i=ith binary digit of key

c_i =ith binary digit of ciphertext

$\oplus$ = exclusive-or (XOR) operation



the ciphertext is generated by performing the bitwise XOR of the plaintext and the key. Because of the properties of the XOR, decryption simply involves the same bitwise operation:

$$pi = ci \oplus ki$$

One-Time Pad

It is an improvement to the Vernam cipher that yields the ultimate in security. In this technique using a random key that is as long as the message, so that the key need not be repeated. In addition, the key is to be 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. Such a scheme, known as a one-time pad, is unbreakable. It 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.

An example should illustrate our point. Suppose that we are using a Vigenère scheme with 27 characters in which the twenty-seventh character is the space character, but with a one-time key that is as long as the message. Consider the ciphertext

```
ANKYODKYUREPFJBYOJDSPLREYIUNOFDOIUERFPLUYTS
```

We now show two different decryptions using two different keys:

```
Ciphertext   : ANKYODKYUREPFJBYOJDSPLREYIUNOFDOIUERFPLUYTS

Key          : pxlmvmsydofuyrvzwc tnlebnecvgdupahfzzlmnyih

Plaintext    : mr mustard with the candlestick in the hall

Ciphertext   : ANKYODKYUREPFJBYOJDSPLREYIUNOFDOIUERFPLUYTS

Key          : mfugpmiydgaxgoufhklllmhsqdqogtewbqfgyovuhwt

Plaintext    : miss scarlet with the knife in the library
```

Two fundamental difficulties:

1. There is the practical problem of making large quantities of random keys.

2. Even more daunting is the problem of key distribution and protection. 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 and is useful primarily for low-bandwidth channels requiring very high security.

II .TRANSPOSITION TECHNIQUES

All the techniques examined so far involve the substitution of a cipher text symbol for a plaintext symbol. A very different kind of mapping is achieved by performing some sort of permutation on the plaintext letters. This technique is referred to as a transposition cipher.

Rail fence is simplest of such cipher, in which the plaintext is written down as a sequence of diagonals and then read off as a sequence of rows.

Example

To encipher the message “meet me after the toga party” with a rail fence of depth 2, we write the following:

```
m e m a t r h t g p r y
 e t e f e t e o a a t
```

The encrypted message is

MEMATRHTGPRYETEFETEOAAT

Row Transposition Ciphers: A more complex scheme is to 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. For example

```
      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
```

Thus, in this example, the key is 4312567.To encrypt, start with the column 1, in this case column 3.Write down all the letters in that column. Proceed to column 4, which is labeled 2, then column 2, then column 1, then columns 5, 6, and 7.

A pure transposition cipher is easily recognized because it has the same letter frequencies as the original plaintext. The transposition cipher can be made significantly more secure by performing more than one stage of transposition. The result is more complex permutation that is not easily reconstructed.

```
Key    : 4 3 1 2 5 6 7
Input  : t t n a a p t
         m t s u o a o
         d w c o i x k
         n l y p e t z
Output: NSCYAUOPTTWLTMDNAOIEPAXTTOKZ
```

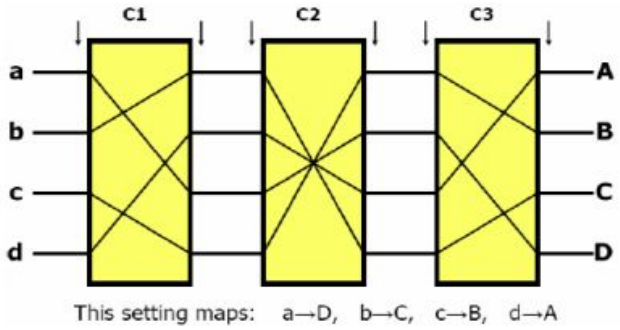
Rotor Machine:

Combine Substitution and Transposition Methods

• produce ciphers that are very difficult to break

Rotor Machines in World War II: German "Enigma" and Japanese "Purple"

• Breaking by the Allies was a significant factor in the outcome of the war (Turing)



STEGANOGRAPHY

A plaintext message may be hidden in any one of the two ways. The methods of steganography conceal the existence of the message, whereas the methods of cryptography render the message unintelligible to outsiders by various transformations of the text.

A simple form of steganography, but one that is time consuming to construct is one in which an arrangement of words or letters within an apparently innocuous text spells out the real message.

e.g., (i) the sequence of first letters of each word of the overall message spells out the real (hidden) message.

(ii) Subset of the words of the overall message is used to convey the hidden message. Various other techniques have been used historically, some of them are

- **Character marking** – selected letters of printed or typewritten text are overwritten in pencil. The marks are ordinarily not visible unless the paper is held to an angle to bright light.
- **Invisible ink** – a number of substances can be used for writing but leave no visible trace until heat or some chemical is applied to the paper.

- **Pin punctures** – small pin punctures on selected letters are ordinarily not visible unless the paper is held in front of the light.
- **Typewritten correction ribbon** – used between the lines typed with a black ribbon, the results of typing with the correction tape are visible only under a strong light.

Drawbacks of steganography

i. Requires a lot of overhead to hide a relatively few bits of information.

ii. Once the system is discovered, it becomes virtually worthless.

BLOCK CIPHERS AND THE DATA ENCRYPTION STANDARD

BLOCK CIPHER PRINCIPLES:

Many symmetric block encryption algorithms in current use are based on a structure referred to as a Feistel block cipher. For that reason, it is important to examine the design principles of the Feistel cipher. We begin with a **comparison of stream ciphers and block ciphers.**

Stream Ciphers and Block Ciphers:

A **stream cipher** is one that encrypts a digital data stream one bit or one byte at a time.

Examples of classical stream ciphers are the autokeyed Vigenère cipher and the Vernam cipher.

block cipher is one in which a block of plaintext is treated as a whole and used to produce a ciphertext block of equal length. Typically, a block size of 64 or 128 bits is used. A block cipher can be used to achieve the same effect as a stream cipher.

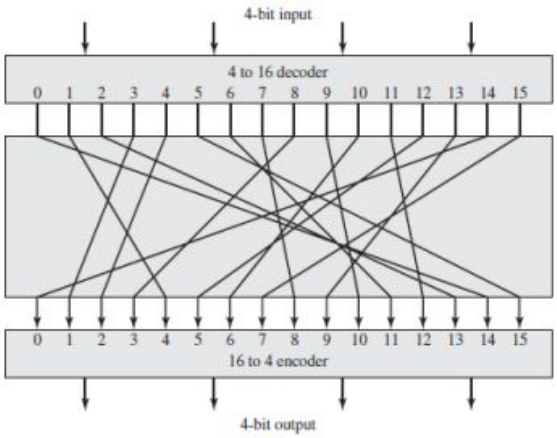
Motivation for the Feistel Cipher Structure:

A block cipher operates on a plaintext block of n bits to produce a ciphertext block of n bits. There are 2^n possible different plaintext blocks and, for the encryption to be reversible (i.e., for decryption to be possible), each must produce a unique ciphertext block. Such a transformation is called reversible, or nonsingular. The following examples illustrate nonsingular and singular transformations for $n = 2$.

Reversible Mapping	
Plaintext	**Ciphertext**
00	11
01	10
10	00
11	01

Irreversible Mapping	
Plaintext	**Ciphertext**
00	11
01	10
10	01
11	01

In the latter case, a ciphertext of 01 could have been produced by one of two plaintext blocks. So if we limit ourselves to reversible mappings, the number of different transformations is $2^n!$.



The logic of a general substitution cipher for n=4. A 4-bit input produces one of 16 possible input states, which is mapped by the substitution cipher into a unique one of 16 possible output states, each of which is represented by 4 ciphertext bits. The encryption and decryption mappings can be defined by tabulation.

This is the most general form of block cipher and can be used to define any reversible mapping between plaintext and ciphertext. Feistel refers to this as the ideal block cipher, because it allows for the maximum number of possible encryption mappings from the plaintext block.

Plaintext	Ciphertext
0000	1110
0001	0100
0010	1101
0011	0001
0100	0010
0101	1111
0110	1011
0111	1000
1000	0011
1001	1010
1010	0110
1011	1100
1100	0101
1101	1001
1110	0000
1111	0111

Ciphertext	Plaintext
0000	1110
0001	0011
0010	0100
0011	1000
0100	0001
0101	1100
0110	1010
0111	1111
1000	0111
1001	1101
1010	1001
1011	0110
1100	1011
1101	0010
1110	0000
1111	0101

But there is a practical problem with the ideal block cipher. If a small block size, such as n=4, is used, then the system is equivalent to a classical substitution cipher. Such systems, as we have seen, are vulnerable to a statistical analysis of the plaintext. This weakness is not inherent in the use of a substitution cipher but rather results from the use of a small block size. If n is sufficiently large and an arbitrary reversible substitution between plaintext and ciphertext is allowed, then the statistical characteristics of the source plaintext are masked to such an extent that this type of cryptanalysis is infeasible

The Feistel Cipher:

• **diffusion** – Statistical structure of the plaintext is dissipates into long-range statistics of the ciphertext
• **confusion** – make the relationship between the statistics of the ciphertext and the value of the encryption key as complex as possible

Feistel cipher structure:

The input to the encryption algorithm are a plaintext block of length 2w bits and a key K. the plaintext block is divided into two halves L0 and R0. The two halves of the data pass through „n" rounds of processing and then combine to produce the ciphertext block. Each round „i" has inputs Li-1 and Ri-1, derived from the previous round, as well as the subkey Ki, derived from the overall key K. in general, the subkeys Ki are different from K and from each other.

All rounds have the same structure. A substitution is performed on the left half of the data (as similar to S-DES). This is done by applying a round function F to the right half of the data and then taking the XOR of the output of that function and the left half of the data. The round function has the same general structure for each round but is parameterized by the round subkey ki. Following this substitution, a permutation is performed that consists of the interchange of the two halves of the data. This structure is a particular form of the substitution-permutation network. The exact realization of a Feistel network depends on the choice of the following parameters and design features:

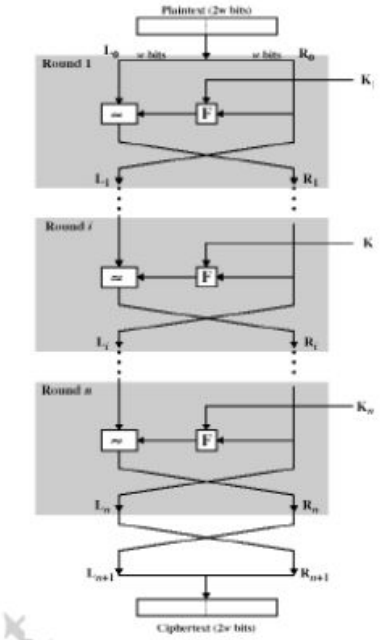
• **Block size:** Larger block sizes mean greater security (all other things being equal) but reduced encryption/decryption speed for a given algorithm. The greater security is achieved by greater diffusion. Traditionally, a block size of 64 bits has been considered a reasonable tradeoff and was nearly universal in block cipher design. However, the new AES uses a 128-bit block size.

• **Key size:** Larger key size means greater security but may decrease encryption/decryption speed. The greater security is achieved by greater resistance to brute-force attacks and greater confusion. Key sizes of 64 bits or less are now widely considered to be inadequate, and 128 bits has become a common size.

• **Number of rounds:** The essence of the Feistel cipher is that a single round offers inadequate security but that multiple rounds offer increasing security. A typical size is 16 rounds.

• **Subkey generation algorithm:** Greater complexity in this algorithm should lead to greater difficulty of cryptanalysis.

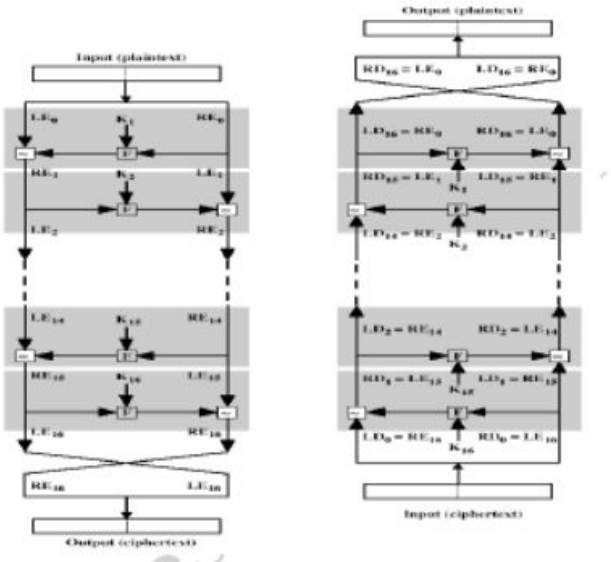
• **Round function F:** Again, greater complexity generally means greater resistance to cryptanalysis.



There are two other considerations in the design of a Feistel cipher:

• **Fast software encryption/decryption:** In many cases, encryption is embedded in applications or utility functions in such a way as to preclude a hardware implementation. Accordingly, the speed of execution of the algorithm becomes a concern.

• **Ease of analysis:** Although we would like to make our algorithm as difficult as possible to cryptanalyze, there is great benefit in making the algorithm easy to analyze.



The process of decryption is essentially the same as the encryption process. The rule is as follows: use the cipher text as input to the algorithm, but use the subkey ki in reverse order. i.e., kn in the first round, kn-1 in second round and so on. For clarity, we use the notation LEi and REi for data traveling through the decryption algorithm. The diagram below indicates that, at each round, the intermediate value of the decryption process is same (equal) to the corresponding value of the encryption process with two halves of the value swapped. i.e.,

$$RE_i \| LE_i \text{ (or) equivalently } RD_{16-i} \| LD_{16-i}$$

After the last iteration of the encryption process, the two halves of the output are swapped, so that the cipher text is RE16 || LE16. The output of that round is the cipher text. Now take the cipher text and use it as input to the same algorithm. The input to the first round is RE16 || LE16, which is equal to the 32-bit swap of the output of the sixteenth round of the encryption process. Now we will see how the output of the first round of the decryption process is equal to a 32-bit swap of the input to the sixteenth round of the encryption process. First consider the encryption process,

$$LE_{16} = RE_{15}$$

$$RE_{16} = LE_{15} \oplus F(RE_{15}, K_{16})$$

On the decryption side,

$$LD_1 = RD_0 = LE_{16} = RE_{15}$$

$$RD_1 = LD_0 \oplus F(RD_0, K_{16})$$

$$= RE_{16} \oplus F(RE_{15}, K_{16})$$

$$= [LE_{15} \oplus F(RE_{15}, K_{16})] \oplus F(RE_{15}, K_{16})$$

$$= LE_{15}$$

Therefore,

$$LD_1 = RE_{15}$$

$$RD_1 = LE_{15}$$

In general, for the i^{th} iteration of the encryption algorithm,

$$LE_i = RE_{i-1}$$

$$RE_i = LE_{i-1} \oplus F(RE_{i-1}, K_i)$$

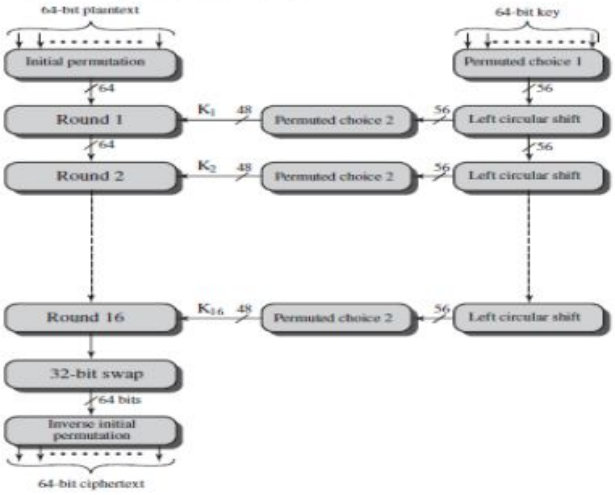
Finally, the output of the last round of the decryption process is $RE_0 \| LE_0$. A 32-bit swap recovers the original plaintext.

DATA ENCRYPTION STANDARD (DES)

The most widely used encryption scheme is based on the Data Encryption Standard (DES) adopted in 1977 by the National Bureau of Standards, now the National Institute of Standards and Technology (NIST), as Federal Information Processing Standard 46 (FIPS PUB 46). The algorithm itself is referred to as the Data Encryption Algorithm (DEA).For DES, data are encrypted in 64-bit blocks using a 56-bit key. The algorithm transforms 64-bit input in a series of steps into a 64-bit output. The same steps, with the same key, are used to reverse the encryption. The DES enjoys widespread use. It has also been the subject of much controversy concerning how secure the DES is.

DES Encryption:

The overall scheme for DES encryption is illustrated in this Figure. As with any encryption scheme, there are two inputs to the encryption function: the plaintext to be encrypted and the key. In this case, the plaintext must be 64 bits in length and the key is 56 bits in length.



Looking at the left-hand side of the figure, we can see that the processing of the plaintext proceeds in three phases. First, the 64-bit plaintext passes through an initial permutation (IP) that rearranges the bits to produce the *permuted input*. This is followed by a phase consisting of sixteen rounds of the same function, which involves both permutation and substitution functions. The output of the last (sixteenth) round consists of 64 bits that are a function of the input plaintext and the key. The left and right halves of the output are swapped to produce the **preoutput**. Finally, the preoutput is passed through a permutation [IP-1] that is the inverse of the initial permutation function, to produce the 64-bit ciphertext.

The right-hand portion of above Figure shows the way in which the 56-bit key is used. Initially, the key is passed through a permutation function. Then, for each of the sixteen rounds, a *subkey* (*Ki*) is produced by the combination of a left circular shift and a permutation. The permutation function is the same for each round, but a different subkey is produced because of the repeated shifts of the key bits.

INITIAL PERMUTATION The initial permutation and its inverse are defined by tables, The tables are to be interpreted as follows. The input to a table consists of 64 bits numbered from 1 to 64. The 64 entries in the permutation table contain a permutation of the numbers from 1 to 64. Each entry in the permutation table indicates the position of a numbered input bit in the output, which also consists of 64 bits.

To see that these two permutation functions are indeed the inverse of each other, consider the following 64-bit input M:

M_1	M_2	M_3	M_4	M_5	M_6	M_7	M_8
M_9	M_{10}	M_{11}	M_{12}	M_{13}	M_{14}	M_{15}	M_{16}
M_{17}	M_{18}	M_{19}	M_{20}	M_{21}	M_{22}	M_{23}	M_{24}
M_{25}	M_{26}	M_{27}	M_{28}	M_{29}	M_{30}	M_{31}	M_{32}
M_{33}	M_{34}	M_{35}	M_{36}	M_{37}	M_{38}	M_{39}	M_{40}
M_{41}	M_{42}	M_{43}	M_{44}	M_{45}	M_{46}	M_{47}	M_{48}
M_{49}	M_{50}	M_{51}	M_{52}	M_{53}	M_{54}	M_{55}	M_{56}
M_{57}	M_{58}	M_{59}	M_{60}	M_{61}	M_{62}	M_{63}	M_{64}

where M_i is a binary digit. Then the permutation $X = (\text{IP}(M)$ is as follows:

M_{58}	M_{50}	M_{42}	M_{34}	M_{26}	M_{18}	M_{10}	M_2
M_{60}	M_{52}	M_{44}	M_{36}	M_{28}	M_{20}	M_{12}	M_4
M_{62}	M_{54}	M_{46}	M_{38}	M_{30}	M_{22}	M_{14}	M_6
M_{64}	M_{56}	M_{48}	M_{40}	M_{32}	M_{24}	M_{16}	M_8
M_{57}	M_{49}	M_{41}	M_{33}	M_{25}	M_{17}	M_9	M_1
M_{59}	M_{51}	M_{43}	M_{35}	M_{27}	M_{19}	M_{11}	M_3
M_{61}	M_{53}	M_{45}	M_{37}	M_{29}	M_{21}	M_{13}	M_5
M_{63}	M_{55}	M_{47}	M_{39}	M_{31}	M_{23}	M_{15}	M_7

If we then take the inverse permutation $Y = \text{IP-1}(X) = \text{IP-1}(\text{IP}(M))$, it can be seen that the original ordering of the bits is restored.

(a) Initial Permutation (IP)

58	50	42	34	26	18	10	2
60	52	44	36	28	20	12	4
62	54	46	38	30	22	14	6
64	56	48	40	32	24	16	8
57	49	41	33	25	17	9	1
59	51	43	35	27	19	11	3
61	53	45	37	29	21	13	5
63	55	47	39	31	23	15	7

(b) Inverse Initial Permutation (IP^{-1})

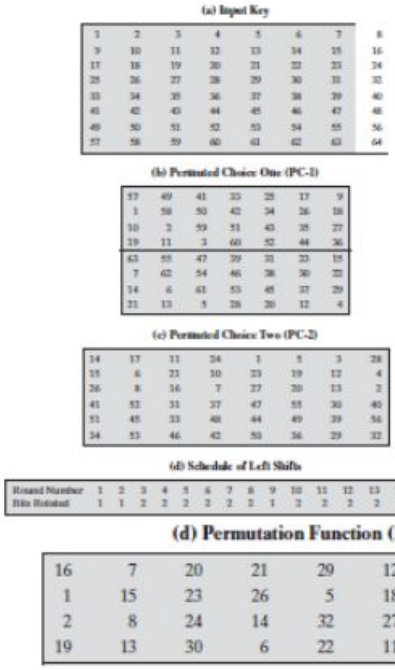
40	8	48	16	56	24	64	32
39	7	47	15	55	23	63	31
38	6	46	14	54	22	62	30
37	5	45	13	53	21	61	29
36	4	44	12	52	20	60	28
35	3	43	11	51	19	59	27
34	2	42	10	50	18	58	26
33	1	41	9	49	17	57	25

(c) Expansion Permutation (E)

32	1	2	3	4	5
4	5	6	7	8	9
8	9	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	30	31	32	1

- Initially the key is passed through a permutation function (PC_1)
- For each of the 16 iterations, a subkey (K_i) is produced by a combination of a left circular shift and a permutation (

$PC_{2)}$ which is the same for each iteration. However, the resulting subkey is different for each iteration because of repeated shifts



(a) Input Key

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	26	27	28	29	30	31	32
33	34	35	36	37	38	39	40
41	42	43	44	45	46	47	48
49	50	51	52	53	54	55	56
57	58	59	60	61	62	63	64

(b) Permuted Choice One (PC-1)

57	49	41	33	25	17	9
1	58	50	42	34	26	18
10	2	59	51	43	35	27
19	11	3	60	52	44	36
63	55	47	39	31	23	15
7	62	54	46	38	30	22
14	6	61	53	45	37	29
21	13	5	28	20	12	4

(c) Permuted Choice Two (PC-2)

14	17	11	24	1	5	3	28
15	6	21	10	23	19	12	4
26	8	16	7	27	20	13	2
41	52	31	37	47	55	30	40
51	45	33	48	44	49	39	56
34	53	46	42	50	36	29	32

(d) Schedule of Left Shifts

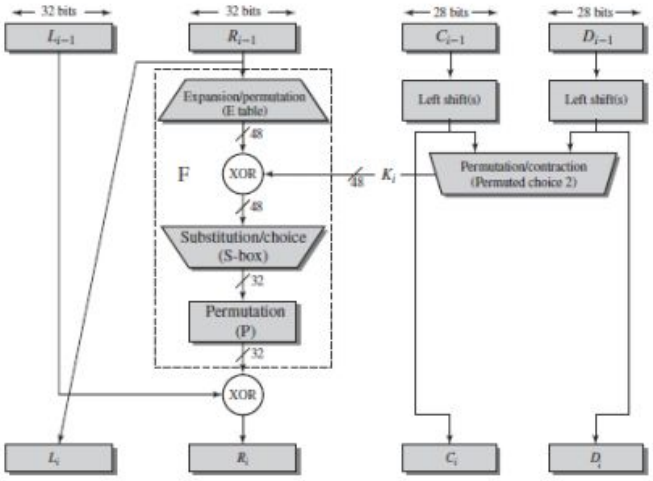
Round Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Bits Rotated	1	1	2	2	2	2	2	2	1	2	2	2	2	2	2	1

(d) Permutation Function (P)

16	7	20	21	29	12	28	17
1	15	23	26	5	18	31	10
2	8	24	14	32	27	3	9
19	13	30	6	22	11	4	25

DETAILS OF SINGLE ROUND Below Figure shows the internal structure of a single round. Again, begin by focusing on the left-hand side of the diagram. The left and right halves of each 64-bit intermediate value are treated as separate 32-bit quantities, labeled L (left) and R (right). As in any classic Feistel cipher, the overall processing at each round can be summarized in the following formulas

$$L_i = R_{i-1}$$
$$R_i = L_{i-1} \oplus F(R_{i-1}, K_i)$$



The E-box expansion permutation - here the 32-bit input data from R_{i-1} is expanded and permuted to give the 48 bits necessary for combination with the 48 bit key (defined in table 2.1). The E-box expansion permutation delivers a larger output by splitting its input into 8, 4-bit blocks and copying every first and fourth bit in each block into the output in a defined manner. The security offered by this operation comes from one bit affecting two substitutions in the S-boxes. This causes the dependency of the output bits on the input bits to spread faster, and is known as the avalanche affect.

2. The bit by bit addition modulo 2 (or exclusive OR) of the E-box output and 48 bit subkey K_i.

3. The S-box substitution - this is a highly important substitution which accepts a 48-bit input and outputs a 32-bit number (defined in table 2.3). The S-boxes are the only non-linear operation in DES and are therefore the most important part of its security. They were very carefully designed although the conditions they were designed under has been under intense scrutiny since DES was released. The reason was because IBM had already designed a set of S-boxes which were completely changed by the NSA with no explanation why.

The input to the S-boxes is 48 bits long arranged into 8, 6 bit blocks ($b_1, b_2, \ldots, b_6$). There are 8 S-boxes ($S_1, S_2, \ldots, S_8$) each of which accepts one of the 6 bit blocks. The output of each S-box is a four bit number. Each of the S-boxes can be thought of as a 4×16 matrix. Each cell of the matrix is identified by a coordinate pair (i, j), where $0 \leq I \leq 3$ and $0 \leq j \leq 15$. The value of i is taken as the decimal representation of the first and last bits of the input to each S-box, i.e. Dec (b_1b_6) =iand the value of j is take from the decimal representation of the inner four bits that remain, S-box matrices contains a 4-bit number which is output once that particular cell is selected by the input.

4. The P-box permutation - This simply permutes the output of the S-box without changing the size of the data (defined in table 2.1). It is simply a permutation and nothing else. It has a one to one mapping of its input to its output giving a 32 bit output from a 32 bit input.

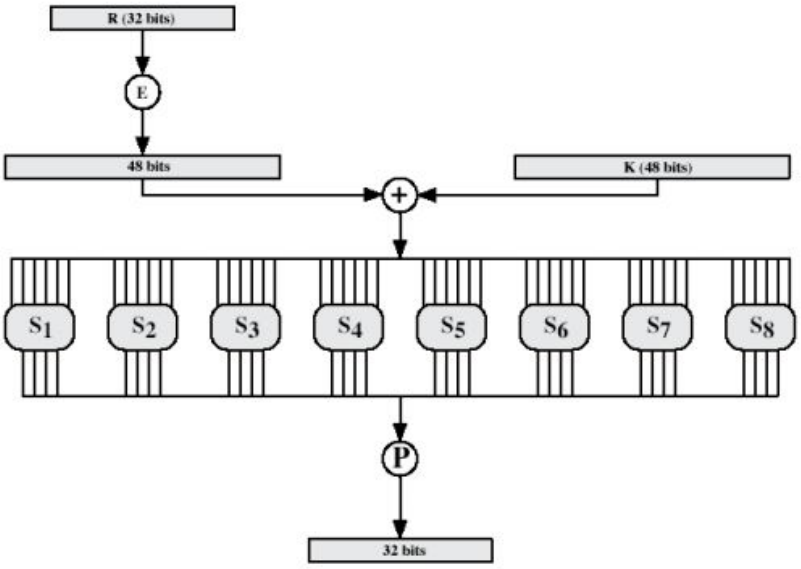


Figure 3.9 Calculation of F(R, K)

Table 3.3 Definition of DES S-Boxes

S_1	14	4	13	1	2	15	11	8	3	10	6	12	5	9	0	7
	0	15	7	4	14	2	13	1	10	6	12	11	9	5	3	8
	4	1	14	8	13	6	2	11	15	12	9	7	3	10	5	0
	15	12	8	2	4	9	1	7	5	11	3	14	10	0	6	13
S_2	15	1	8	14	6	11	3	4	9	7	2	13	12	0	5	10
	3	13	4	7	15	2	8	14	12	0	1	10	6	9	11	5
	0	14	7	11	10	4	13	1	5	8	12	6	9	3	2	15
	13	8	10	1	3	15	4	2	11	6	7	12	0	5	14	9
S_3	10	0	9	14	6	3	15	5	1	13	12	7	11	4	2	8
	13	7	0	9	3	4	6	10	2	8	5	14	12	11	15	1
	13	6	4	9	8	15	3	0	11	1	2	12	5	10	14	7
	1	10	13	0	6	9	8	7	4	15	14	3	11	5	2	12
S_4	7	13	14	3	0	6	9	10	1	2	8	5	11	12	4	15
	13	8	11	5	6	15	0	3	4	7	2	12	1	10	14	9
	10	6	9	0	12	11	7	13	15	1	3	14	5	2	8	4
	3	15	0	6	10	1	13	8	9	4	5	11	12	7	2	14
S_5	2	12	4	1	7	10	11	6	8	5	3	15	13	0	14	9
	14	11	2	12	4	7	13	1	5	0	15	10	3	9	8	6
	4	2	1	11	10	13	7	8	15	9	12	5	6	3	0	14
	11	8	12	7	1	14	2	13	6	15	0	9	10	4	5	3
S_6	12	1	10	15	9	2	6	8	0	13	3	4	14	7	5	11
	10	15	4	2	7	12	9	5	6	1	13	14	0	11	3	8
	9	14	15	5	2	8	12	3	7	0	4	10	1	13	11	6
	4	3	2	12	9	5	15	10	11	14	1	7	6	0	8	13
S_7	4	11	2	14	15	0	8	13	3	12	9	7	5	10	6	1
	13	0	11	7	4	9	1	10	14	3	5	12	2	15	8	6
	1	4	11	13	12	3	7	14	10	15	6	8	0	5	9	2
	6	11	13	8	1	4	10	7	9	5	0	15	14	2	3	12
S_8	13	2	8	4	6	15	11	1	10	9	3	14	5	0	12	7
	1	15	13	8	10	3	7	4	12	5	6	11	0	14	9	2
	7	11	4	1	9	12	14	2	0	6	10	13	15	3	5	8
	2	1	14	7	4	10	8	13	15	12	9	0	3	5	6	11

Each row of an S-box defines a general reversible substitution: middle 4 bits of each group of 6-bit input are substituted by S-box output, 1st and last 6th bits define what particular substitution out of to use.

DES decryption:

As with any feistel cipher, decryption uses the same algorithm as encryption, except that the application of the subkeys is reverse.

Avalanche effect

A desirable property of any encryption algorithm is that a small change in either plaintext or key should produce significant changes in the ciphertext. DES exhibits a strong avalanche effect.

(a) Change in Plaintext		(b) Change in Key	
Round	Number of bits that differ	Round	Number of bits that differ
0	1	0	0
1	6	1	2
2	21	2	14
3	35	3	28
4	39	4	32
5	34	5	30
6	32	6	32
7	31	7	35
8	29	8	34
9	42	9	40
10	44	10	38
11	32	11	31
12	30	12	33
13	30	13	28
14	26	14	26
15	29	15	34
16	34	16	35

Avalanche effect - a small change in the plaintext produces a significant change in the ciphertext.

Strength of DES
The Use of 56-Bit Keys

- With a key length of 56 bits, there are 2^{56} possible keys, which is approximately 7.2×10^{16}. Brute force search looks hard.
- DES finally and definitively proved insecure in July 1998, when the Electronic Frontier Foundation (EFF) announced that it had broken a DES encryption using a special-purpose "DES cracker" machine. The attack took less than three days.
- Alternatives to DES are required-which are AES and triple DES.

The Nature of the DES Algorithm

- Another concern is the possibility that cryptanalysis is possible by exploiting the characteristics of the DES algorithm.
- The focus of concern has been on the eight substitution tables, or S-boxes, that are used in each iteration.
- No one has so far succeeded in discovering the supposed fatal weaknesses in the S-boxes.

Timing Attacks

- A timing attack is one in which information about the key or the plaintext is obtained by observing how long it takes a given implementation to perform decryptions on various cipher texts.
- A timing attack exploits the fact that an encryption or decryption algorithm often takes slightly different amounts of time on different inputs.
- DES is resistant to a successful timing attack.

Cryptanalytic attacks on DES

- **Differential cryptanalysis**

- Initially- less than 2^{55} encryptions
- cryptanalyze DES with an effort on the order of 2^{47} encryptions, requiring 2^{47} chosen plaintexts.
- Differential cryptanalysis is to observe the behavior of pairs of text blocks evolving along each round of the cipher.

- Many pairs of inputs to f with the same difference yield the same output difference if the same subkey is used.
- Linear analysis-This method can find a DES key given known 2^{43} plaintexts, as compared to 2^{47} chosen plaintexts for differential cryptanalysis.
- The need to strengthen DES against attacks using differential cryptanalysis played a large part in the design of the S-boxes and the permutation P.
- Differential cryptanalysis of an eight-round LUCIFER algorithm requires only 256 chosen plaintexts, whereas an attack on an eight-round version of DES requires 2^{14} chosen plaintexts.
- **Linear cryptanalysis**

The objective of linear cryptanalysis is to find an effective *linear* equation of the form:

$$P[\alpha_1, \alpha_2, \ldots, \alpha_a] \oplus C[\beta_1, \beta_2, \ldots, \beta_b] = K[\gamma_1, \gamma_2, \ldots, \gamma_c]$$

-

BLOCK CIPHERS AND THE DATA ENCRYPTION STANDARD BLOCK CIPHER PRINCIPLES:

Many symmetric block encryption algorithms in current use are based on a structure referred to as a Feistel block cipher. For that reason, it is important to examine the design principles of the Feistel cipher. We begin with a **comparison of stream ciphers and block ciphers.**

Stream Ciphers and Block Ciphers:

A **stream cipher** is one that encrypts a digital data stream one bit or one byte at a time.

Examples of classical stream ciphers are the autokeyed Vigenère cipher and the Vernam cipher.

block cipher is one in which a block of plaintext is treated as a whole and used to produce a ciphertext block of equal length. Typically, a block size of 64 or 128 bits is used. A block cipher can be used to achieve the same effect as a stream cipher.

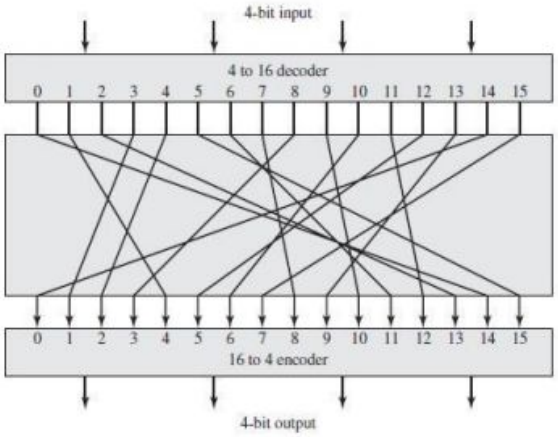
Motivation for the Feistel Cipher Structure:

A block cipher operates on a plaintext block of n bits to produce a ciphertext block of n bits. There are 2^n possible different plaintext blocks and, for the encryption to be reversible (i.e., for decryption to be possible), each must produce a unique ciphertext block. Such a transformation is called reversible, or nonsingular. The following examples illustrate nonsingular and singular transformations for $n = 2$.

Reversible Mapping	
Plaintext	**Ciphertext**
00	11
01	10
10	00
11	01

Irreversible Mapping	
Plaintext	**Ciphertext**
00	11
01	10
10	01
11	01

In the latter case, a ciphertext of 01 could have been produced by one of two plaintext blocks. So if we limit ourselves to reversible mappings, the number of different transformations is $2^n!$.



The logic of a general substitution cipher for n=4. A 4-bit input produces one of 16 possible input states, which is mapped by the substitution cipher into a unique one of 16 possible output states, each of which is represented by 4 ciphertext bits. The encryption and decryption mappings can be defined by tabulation.

This is the most general form of block cipher and can be used to define any reversible mapping between plaintext and ciphertext. Feistel refers to this as the ideal block cipher, because it allows for the maximum number of possible encryption mappings from the plaintext block.

Plaintext	Ciphertext
0000	1110
0001	0100
0010	1101
0011	0001
0100	0010
0101	1111
0110	1011
0111	1000
1000	0011
1001	1010
1010	0110
1011	1100
1100	0101
1101	1001
1110	0000
1111	0111

Ciphertext	Plaintext
0000	1110
0001	0011
0010	0100
0011	1000
0100	0001
0101	1100
0110	1010
0111	1111
1000	0111
1001	1101
1010	1001
1011	0110
1100	1011
1101	0010
1110	0000
1111	0101

But there is a practical problem with the ideal block cipher. If a small block size, such as n=4, is used, then the system is equivalent to a classical substitution cipher. Such systems, as we have seen, are vulnerable to a statistical analysis of the plaintext. This weakness is not inherent in the use of a substitution cipher but rather results from the use of a small block size. If n is sufficiently large and an arbitrary reversible substitution between plaintext and ciphertext is allowed, then the statistical characteristics of the source plaintext are masked to such an extent that this type of cryptanalysis is infeasible

The Feistel Cipher:

- **diffusion** – dissipates statistical structure of plaintext over bulk of ciphertext
- **confusion** – makes relationship between ciphertext and key as complex as possible

Feistel cipher structure:

The input to the encryption algorithm are a plaintext block of length 2w bits and a key K. the plaintext block is divided into two halves L0 and R0. The two halves of the data pass through „n" rounds of processing and then combine to produce the ciphertext block. Each round „i" has inputs Li-1 and Ri-1, derived from the previous round, as well as the subkey Ki, derived from the overall key K. in general, the subkeys Ki are different from K and from each other.

All rounds have the same structure. A substitution is performed on the left half of the data (as similar to S-DES). This is done by applying a round function F to the right half of the data and then taking the XOR of the output of that function and the left half of the data. The round function has the same general structure for each round but is parameterized by the round subkey ki. Following this substitution, a permutation is performed that consists of the interchange of the two halves of the data. This structure is a particular form of the substitution-permutation network. The exact realization of a Feistel network depends on the choice of the following parameters and design features:

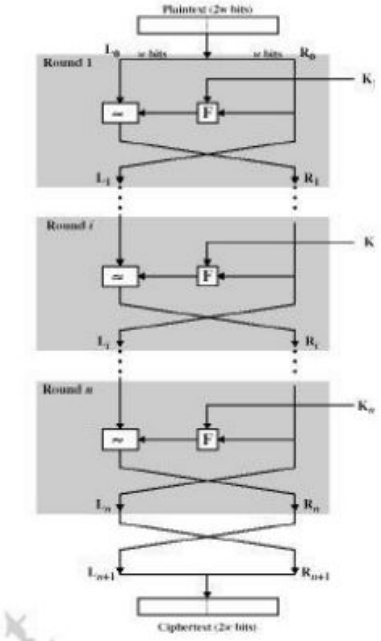
• **Block size:** Larger block sizes mean greater security (all other things being equal) but reduced encryption/decryption speed for a given algorithm. The greater security is achieved by greater diffusion. Traditionally, a block size of 64 bits has been considered a reasonable tradeoff and was nearly universal in block cipher design. However, the new AES uses a 128-bit block size.

• **Key size:** Larger key size means greater security but may decrease encryption/decryption speed. The greater security is achieved by greater resistance to brute-force attacks and greater confusion. Key sizes of 64 bits or less are now widely considered to be inadequate, and 128 bits has become a common size.

• **Number of rounds:** The essence of the Feistel cipher is that a single round offers inadequate security but that multiple rounds offer increasing security. A typical size is 16 rounds.

• **Subkey generation algorithm:** Greater complexity in this algorithm should lead to greater difficulty of cryptanalysis.

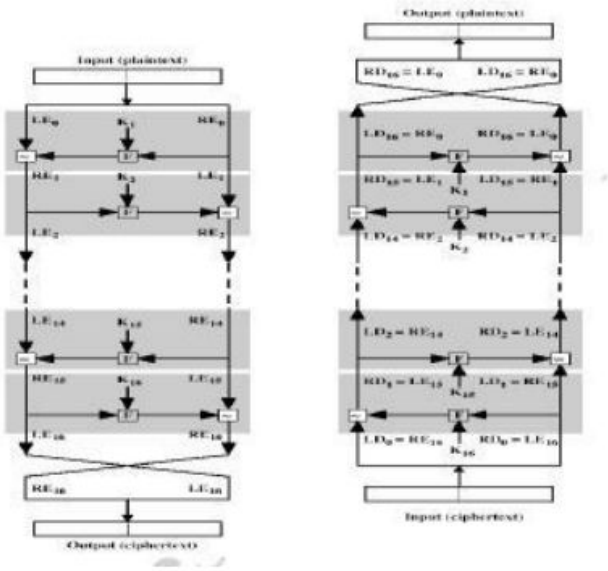
• **Round function F:** Again, greater complexity generally means greater resistance to cryptanalysis.



There are two other considerations in the design of a Feistel cipher:

• **Fast software encryption/decryption:** In many cases, encryption is embedded in applications or utility functions in such a way as to preclude a hardware implementation. Accordingly, the speed of execution of the algorithm becomes a concern.

• **Ease of analysis:** Although we would like to make our algorithm as difficult as possible to cryptanalyze, there is great benefit in making the algorithm easy to analyze.



The process of decryption is essentially the same as the encryption process. The rule is as follows: use the cipher text as input to the algorithm, but use the subkey ki in reverse order. i.e., kn in the first round, kn-1 in second round and so on. For clarity, we use the notation LEi and REi for data traveling through the decryption algorithm. The diagram below indicates that, at each round, the intermediate value of the decryption process is same (equal) to the corresponding value of the encryption process with two halves of the value swapped. i.e.,

$$RE_i \,||\, LE_i \text{ (or) equivalently } RD_{16-i} \,||\, LD_{16-i}$$

After the last iteration of the encryption process, the two halves of the output are swapped, so that the cipher text is RE16 || LE16. The output of that round is the cipher text. Now take the cipher text and use it as input to the same algorithm. The input to the first round is RE16 || LE16, which is equal to the 32-bit swap of the output of the sixteenth round of the encryption process. Now we will see how the output of the first round of the decryption process is equal to a 32-bit swap of the input to the sixteenth round of the encryption process. First consider the encryption process,

$$LE16 = RE15$$
$$RE16 = LE15 \oplus F(RE15, K16)$$

On the decryption side,

$$\begin{aligned} LD1 &= RD0 = LE16 = RE15 \\ RD1 &= LD0 \oplus F(RD0, K16) \\ &= RE16 \oplus F(RE15, K16) \\ &= [LE15 \oplus F(RE15, K16)] \oplus F(RE15, K16) \\ &= LE15 \end{aligned}$$

Therefore, $LD1 = RE15$

$RD1 = LE15$

In general, for the i^{th} iteration of the encryption algorithm,

$$LEi = REi\text{-}1$$
$$REi = LEi\text{-}1 \oplus F(REi\text{-}1, Ki)$$

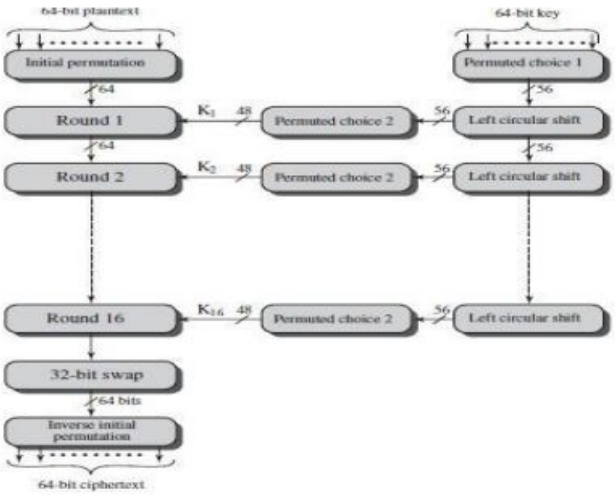
Finally, the output of the last round of the decryption process is $RE_0 \| LE_0$. A 32-bit swap recovers the original plaintext.

DATA ENCRYPTION STANDARD (DES)

The most widely used encryption scheme is based on the Data Encryption Standard (DES) adopted in 1977 by the National Bureau of Standards, now the National Institute of Standards and Technology (NIST), as Federal Information Processing Standard 46 (FIPS PUB 46). The algorithm itself is referred to as the Data Encryption Algorithm (DEA).7 For DES, data are encrypted in 64-bit blocks using a 56-bit key. The algorithm transforms 64-bit input in a series of steps into a 64-bit output. The same steps, with the same key, are used to reverse the encryption. The DES enjoys widespread use. It has also been the subject of much controversy concerning how secure the DES is. To appreciate the nature of the controversy, let us quickly review the history of the DES.

DES Encryption:

The overall scheme for DES encryption is illustrated in this Figure. As with any encryption scheme, there are two inputs to the encryption function: the plaintext to be encrypted and the key. In this case, the plaintext must be 64 bits in length and the key is 56 bits in length.



Looking at the left-hand side of the figure, we can see that the processing of the plaintext proceeds in three phases. First, the 64-bit plaintext passes through an initial permutation (IP) that rearranges the bits to produce the *permuted input*. This is followed by a phase consisting of sixteen rounds of the same function, which involves both permutation and substitution functions. The output of the last (sixteenth) round consists of 64 bits that are a function of the input plaintext and the key. The left and right halves of the output are swapped to produce the **preoutput**. Finally, the preoutput is passed through a permutation [IP-1] that is the inverse of the initial permutation function, to produce the 64-bit ciphertext.

The right-hand portion of above Figure shows the way in which the 56-bit key is used. Initially, the key is passed through a permutation function. Then, for each of the sixteen rounds, a *subkey* (*Ki*) is produced by the combination of a left circular shift and a permutation. The permutation function is the same for each round, but a different subkey is produced because of the repeated shifts of the key bits.

INITIAL PERMUTATION The initial permutation and its inverse are defined by tables, The tables are to be interpreted as follows. The input to a table consists of 64 bits numbered from 1 to 64. The 64 entries in the permutation table contain a permutation of the numbers from 1 to 64. Each entry in the permutation table indicates the position of a numbered input bit in the output, which also consists of 64 bits.

To see that these two permutation functions are indeed the inverse of each other, consider the following 64-bit input M:

$$\begin{matrix} M_1 & M_2 & M_3 & M_4 & M_5 & M_6 & M_7 & M_8 \\ M_9 & M_{10} & M_{11} & M_{12} & M_{13} & M_{14} & M_{15} & M_{16} \\ M_{17} & M_{18} & M_{19} & M_{20} & M_{21} & M_{22} & M_{23} & M_{24} \\ M_{25} & M_{26} & M_{27} & M_{28} & M_{29} & M_{30} & M_{31} & M_{32} \\ M_{33} & M_{34} & M_{35} & M_{36} & M_{37} & M_{38} & M_{39} & M_{40} \\ M_{41} & M_{42} & M_{43} & M_{44} & M_{45} & M_{46} & M_{47} & M_{48} \\ M_{49} & M_{50} & M_{51} & M_{52} & M_{53} & M_{54} & M_{55} & M_{56} \\ M_{57} & M_{58} & M_{59} & M_{60} & M_{61} & M_{62} & M_{63} & M_{64} \end{matrix}$$

where M_i is a binary digit. Then the permutation $X = (\mathrm{IP}(M)$ is as follows:

$$\begin{matrix} M_{58} & M_{50} & M_{42} & M_{34} & M_{26} & M_{18} & M_{10} & M_2 \\ M_{60} & M_{52} & M_{44} & M_{36} & M_{28} & M_{20} & M_{12} & M_4 \\ M_{62} & M_{54} & M_{46} & M_{38} & M_{30} & M_{22} & M_{14} & M_6 \\ M_{64} & M_{56} & M_{48} & M_{40} & M_{32} & M_{24} & M_{16} & M_8 \\ M_{57} & M_{49} & M_{41} & M_{33} & M_{25} & M_{17} & M_9 & M_1 \\ M_{59} & M_{51} & M_{43} & M_{35} & M_{27} & M_{19} & M_{11} & M_3 \\ M_{61} & M_{53} & M_{45} & M_{37} & M_{29} & M_{21} & M_{13} & M_5 \\ M_{63} & M_{55} & M_{47} & M_{39} & M_{31} & M_{23} & M_{15} & M_7 \end{matrix}$$

If we then take the inverse permutation $Y = \mathrm{IP}\text{-}1(X) = \mathrm{IP}\text{-}1(\mathrm{IP}(M))$, it can be seen that the original ordering of the bits is restored.

(a) Initial Permutation (IP)

58	50	42	34	26	18	10	2
60	52	44	36	28	20	12	4
62	54	46	38	30	22	14	6
64	56	48	40	32	24	16	8
57	49	41	33	25	17	9	1
59	51	43	35	27	19	11	3
61	53	45	37	29	21	13	5
63	55	47	39	31	23	15	7

(b) Inverse Initial Permutation (IP^{-1})

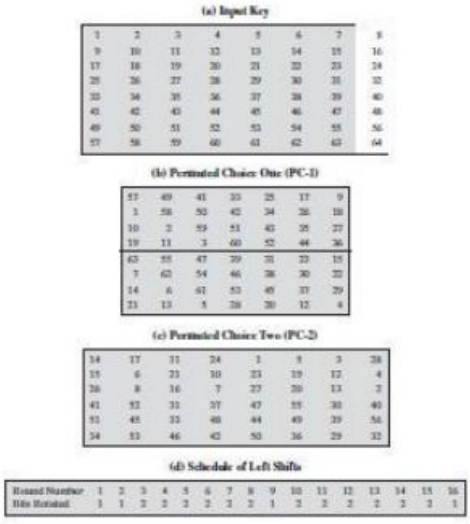
40	8	48	16	56	24	64	32
39	7	47	15	55	23	63	31
38	6	46	14	54	22	62	30
37	5	45	13	53	21	61	29
36	4	44	12	52	20	60	28
35	3	43	11	51	19	59	27
34	2	42	10	50	18	58	26
33	1	41	9	49	17	57	25

(c) Expansion Permutation (E)

32	1	2	3	4	5
4	5	6	7	8	9
8	9	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	30	31	32	1

• Initially the key is passed through a permutation function (PC_1)

• For each of the 16 iterations, a subkey (K_i) is produced by a combination of a left circular shift and a permutation (PC_2) which is the same for each iteration. However, the resulting subkey is different for each iteration because of repeated shifts

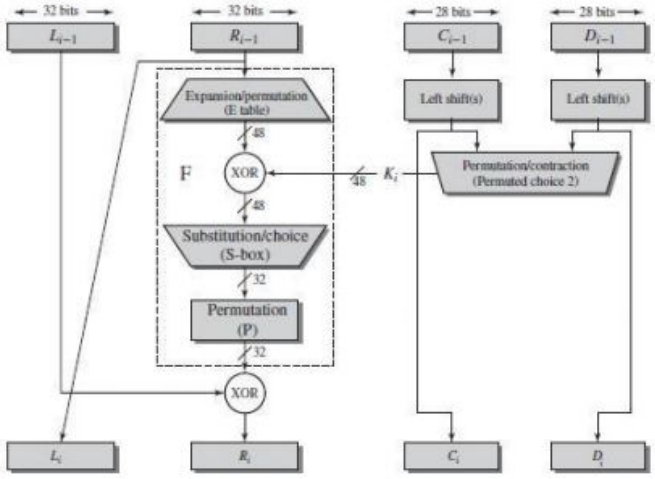


(d) Permutation Function (P)

16	7	20	21	29	12	28	17
1	15	23	26	5	18	31	10
2	8	24	14	32	27	3	9
19	13	30	6	22	11	4	25

DETAILS OF SINGLE ROUND Below Figure shows the internal structure of a single round. Again, begin by focusing on the left-hand side of the diagram. The left and right halves of each 64-bit intermediate value are treated as separate 32-bit quantities, labeled L (left) and R (right). As in any classic Feistel cipher, the overall processing at each round can be summarized in the following formulas

$$L_i = R_{i-1}$$
$$R_i = L_{i-1} \oplus F(R_{i-1}, K_i)$$



The E-box expansion permutation - here the 32-bit input data from R_{i-1} is expanded and permuted to give the 48 bits necessary for combination with the 48 bit key (defined in table 2.1). The E-box expansion permutation delivers a larger output by splitting its input into 8, 4-bit blocks and copying every first and fourth bit in each block into the output in a defined manner. The security offered by this operation comes from one bit affecting two substitutions in the S-boxes. This causes the dependency of the output bits on the input bits to spread faster, and is known as the avalanche affect.

2. The bit by bit addition modulo 2 (or exclusive OR) of the E-box output and 48 bit subkey K_i.

3. The S-box substitution - this is a highly important substitution which accepts a 48-bit input and outputs a 32-bit number (defined in table 2.3). The S-boxes are the only non-linear operation in DES and are therefore the most important part of its security. They were very carefully designed although the conditions they were designed under

has been under intense scrutiny since DES was released. The reason was because IBM had already designed a set of S-boxes which were completely changed by the NSA with no explanation why.

The input to the S-boxes is 48 bits long arranged into 8, 6 bit blocks ($b_1, b_2, \ldots, b_6$). There are 8 S-boxes ($S_1, S_2, \ldots, S_8$) each of which accepts one of the 6 bit blocks. The output of each S-box is a four bit number. Each of the S-boxes can be thought of as a 4×16 matrix. Each cell of the matrix is identified by a coordinate pair (i, j), where $0 \leq I \leq 3$ and $0 \leq j \leq 15$. The value of i is taken as the decimal representation of the first and last bits of the input to each S-box, i.e. Dec (b_1b_6) =iand the value of j is take from the decimal representation of the inner four bits that remain, S-box matrices contains a 4-bit number which is output once that particular cell is selected by the input.

4. The P-box permutation - This simply permutes the output of the S-box without changing the size of the data (defined in table 2.1). It is simply a permutation and nothing else. It has a one to one mapping of its input to its output giving a 32 bit output from a 32 bit input.

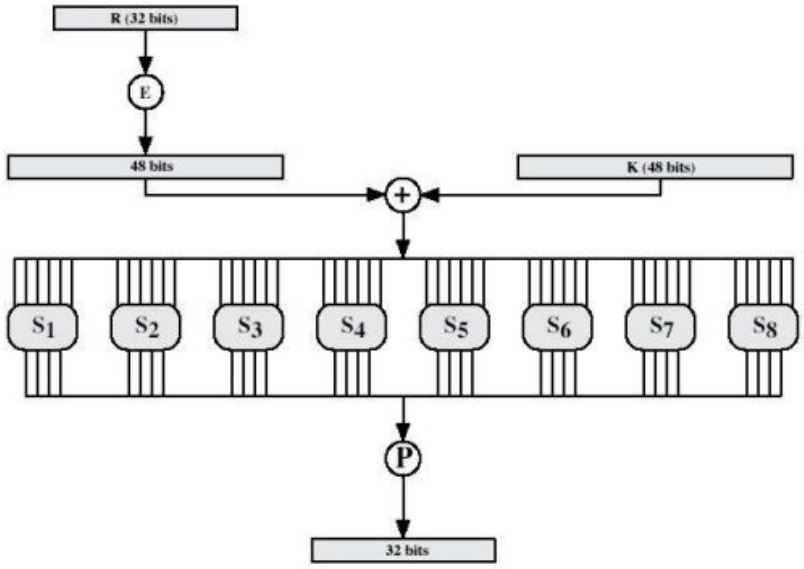


Figure 3.9 Calculation of F(R, K)

Table 3.3 Definition of DES S-Boxes

S_1	14	4	13	1	2	15	11	8	3	10	6	12	5	9	0	7
	0	15	7	4	14	2	13	1	10	6	12	11	9	5	3	8
	4	1	14	8	13	6	2	11	15	12	9	7	3	10	5	0
	15	12	8	2	4	9	1	7	5	11	3	14	10	0	6	13
S_2	15	1	8	14	6	11	3	4	9	7	2	13	12	0	5	10
	3	13	4	7	15	2	8	14	12	0	1	10	6	9	11	5
	0	14	7	11	10	4	13	1	5	8	12	6	9	3	2	15
	13	8	10	1	3	15	4	2	11	6	7	12	0	5	14	9
S_3	10	0	9	14	6	3	15	5	1	13	12	7	11	4	2	8
	13	7	0	9	3	4	6	10	2	8	5	14	12	11	15	1
	13	6	4	9	8	15	3	0	11	1	2	12	5	10	14	7
	1	10	13	0	6	9	8	7	4	15	14	3	11	5	2	12
S_4	7	13	14	3	0	6	9	10	1	2	8	5	11	12	4	15
	13	8	11	5	6	15	0	3	4	7	2	12	1	10	14	9
	10	6	9	0	12	11	7	13	15	1	3	14	5	2	8	4
	3	15	0	6	10	1	13	8	9	4	5	11	12	7	2	14
S_5	2	12	4	1	7	10	11	6	8	5	3	15	13	0	14	9
	14	11	2	12	4	7	13	1	5	0	15	10	3	9	8	6
	4	2	1	11	10	13	7	8	15	9	12	5	6	3	0	14
	11	8	12	7	1	14	2	13	6	15	0	9	10	4	5	3
S_6	12	1	10	15	9	2	6	8	0	13	3	4	14	7	5	11
	10	15	4	2	7	12	9	5	6	1	13	14	0	11	3	8
	9	14	15	5	2	8	12	3	7	0	4	10	1	13	11	6
	4	3	2	12	9	5	15	10	11	14	1	7	6	0	8	13
S_7	4	11	2	14	15	0	8	13	3	12	9	7	5	10	6	1
	13	0	11	7	4	9	1	10	14	3	5	12	2	15	8	6
	1	4	11	13	12	3	7	14	10	15	6	8	0	5	9	2
	6	11	13	8	1	4	10	7	9	5	0	15	14	2	3	12
S_8	13	2	8	4	6	15	11	1	10	9	3	14	5	0	12	7
	1	15	13	8	10	3	7	4	12	5	6	11	0	14	9	2
	7	11	4	1	9	12	14	2	0	6	10	13	15	3	5	8
	2	1	14	7	4	10	8	13	15	12	9	0	3	5	6	11

Each row of an S-box defines a general reversible substitution: middle 4 bits of each group of 6-bit input are substituted by S-box output, 1st and last 6th bits define what particular substitution out of to use.

DES decryption:

As with any feistel cipher, decryption uses the same algorithm as encryption, except that the application of the subkeys is reverse.

Avalanche effect

A desirable property of any encryption algorithm is that a small change in either plaintext or key should produce significant changes in the ciphertext. DES exhibits a strong avalanche effect.

(a) Change in Plaintext		(b) Change in Key	
Round	Number of bits that differ	Round	Number of bits that differ
0	1	0	0
1	6	1	2
2	21	2	14
3	35	3	28
4	39	4	32
5	34	5	30
6	32	6	32
7	31	7	35
8	29	8	34
9	42	9	40
10	44	10	38
11	32	11	31
12	30	12	33
13	30	13	28
14	26	14	26
15	29	15	34
16	34	16	35

Avalanche effect - a small change in the plaintext produces a significant change in the ciphertext.

Strength of DES

- 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 a huge cluster of computers over the Internet in a few months
  - in 1998 on dedicated hardware called "DES cracker" by EFF in a few days ($220,000)
  - in 1999 above combined in 22hrs!
- Still must be able to recognize plaintext
- No big flaw for DES algorithms

AES Evaluation

Security:

This refers to the effort required to cryptanalyze an algorithm. The emphasis in the evaluation was on the practicality of the attack. Because the minimum key size for AES is 128 bits, brute-force attacks with current and projected technology were considered impractical. Therefore, the emphasis, with respect to this point, is cryptanalysis other than a brute-force attack.

Cost:

NIST intends AES to be practical in a wide range of applications. Accordingly, AES must have high computational efficiency, so as to be usable in high-speed applications, such as broadband links.

Algorithm and implementation characteristics:

This category includes a variety of considerations, including flexibility; suitability for a variety of hardware and software implementations; and simplicity, which will make an analysis of security more straightforward

Using these criteria, the initial field of 21 candidate algorithms was reduced first to 15 candidates and then to 5 candidates. By the time that a final evaluation had been done the evaluation criteria, as described in [NECH00], had evolved. The following criteria were used in the final evaluation:

General security:

To assess general security, NIST relied on the public security analysis conducted by the cryptographic community. During the course of the three-year evaluation process, a number of cryptographers published their analyses of the strengths and weaknesses of the various candidates. There was particular emphasis on analyzing the candidates with respect to known attacks, such as differential and linear cryptanalysis. However, compared to the analysis of DES, the amount of time and the number of cryptographers devoted to analyzing Rijndael are quite limited. Now that a single AES cipher has been chosen, we can expect to see a more extensive security analysis by the cryptographic community.

Software implementations:

The principal concerns in this category are execution speed, performance across a variety of platforms, and variation of speed with key size.

Restricted-space environments:

In some applications, such as smart cards, relatively small amounts of random-access memory (RAM) and/or read-only memory (ROM) are available for such purposes as code storage (generally in ROM); representation of data objects such as S-boxes (which could be stored in ROM or RAM, depending on whether pre-computation or Boolean representation is used); and subkey storage (in RAM).

Hardware implementations:

Like software, hardware implementations can be optimized for speed or for size. However, in the case of hardware, size translates much more directly into cost than is usually the case for software implementations. Doubling the size of an encryption program may make little difference on a general-purpose computer with a large memory, but doubling the area used in a hardware device typically more than doubles the cost of the device.

Attacks on implementations:

The criterion of general security, discussed in the first bullet, is concerned with cryptanalytic attacks that exploit mathematical properties of the algorithms. There is another class of attacks that use physical measurements conducted during algorithm execution to gather information about quantities such as keys. Such attacks exploit a combination of intrinsic algorithm characteristics and implementation-dependent features. Examples of such attacks are timing attacks and power analysis. Timing attacks are described in. The basic idea behind power analysis [KOCH98,BIHA00] is the observation that the power consumed by a smart card at any particular time during the cryptographic operation is related to the instruction being executed and to the data being processed. For example, multiplication consumes more power than addition, and writing 1s consumes more power than writing 0s.

Encryption versus decryption:

This criterion deals with several issues related to considerations of both encryption and decryption. If the encryption and decryption algorithms differ, then extra space is needed for the decryption. Also, whether the two algorithms are the same or not, there may be timing differences between encryption and decryption.

Key agility:

Key agility refers to the ability to change keys quickly and with a minimum of resources. This includes both subkey computation and the ability to switch between different ongoing security associations when subkeys may already be available.

Other versatility and flexibility:

[NECH00] indicates two areas that fall into this category. Parameter flexibility includes ease of support for other key and block sizes and ease of increasing the number of rounds in order to cope with newly discovered attacks. Implementation flexibility refers to the possibility of optimizing cipher elements for particular environments.

Potential for instruction-level parallelism:

This criterion refers to the ability to exploit ILP features in current and future processors

The AES cipher

Like DES, AES is a symmetric block cipher. This means that it uses the same key for both encryption and decryption. However, AES is quite different from DES in a number of ways. The algorithm Rijndael allows for a variety of block and key sizes and not just the 64 and 56 bits of DES' block and key size. However, the AES standard states that the algorithm can only accept a block size of 128 bits and a choice of three keys - 128, 192 , 256 bits. Depending on which version is used, the name of the standard is modified to AES-128, AES-192 or AES- 256 respectively. As well as these differences AES differs from DES in that it is not a feistel structure. Recall that in a feistel structure, half of the data block is used to modify the other half of the data block and then the halves are swapped. In this case the entire data block is processed in parallel during each round using substitutions and permutations.

A number of AES parameters depend on the key length. For example, if the key size used is 128 then the number of rounds is 10 whereas it is 12 and 14 for 192 and 256 bits respectively. At present the most common key size likely to be used is the 128 bit key. This description of the AES algorithm therefore describes this particular implementation.

Rijndael was designed to have the following characteristics:

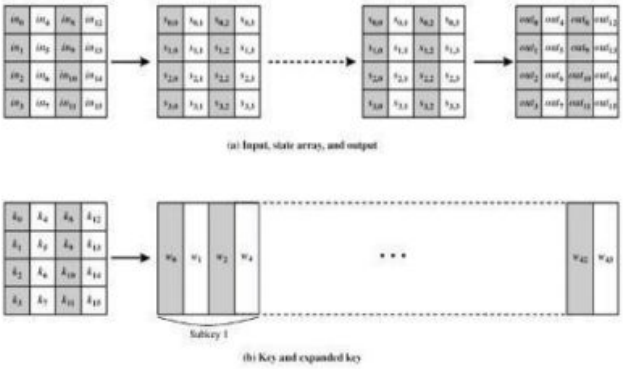
• Resistance against all known attacks.

•Speed and code compactness on a wide range of platforms.

•Design Simplicity.

The overall structure of AES is given below. The input is a single 128 bit block both for decryption and encryption and is known as the in matrix. This block is copied into a state array which is modified at each stage of the algorithm and then copied to an output matrix. Both the plaintext and key are depicted as a 128 bit square matrix of bytes. This

key is then expanded into an array of key schedule words(the w matrix). It must be noted that the ordering of bytes within the in matrix is by column. The same applies to the w matrix.



Before delving into details, we can make several comments about the overall AES structure.

1. AES structure is not a Feistel Structure

2. The key that is provided as input is expanded into an array of forty-four 32-bit words, w[i]. Four distinct words (128 bits) serve as a round key for each round.

3. Four different stages are used, one of permutation and three of substitution:
• Substitute bytes: Uses an S-box to perform a byte-by-byte substitution of the block
• ShiftRows: A simple permutation
• MixColumns: A substitution that makes use of arithmetic over
• AddRoundKey: A simple bitwise XOR of the current block with a portion of the expanded key

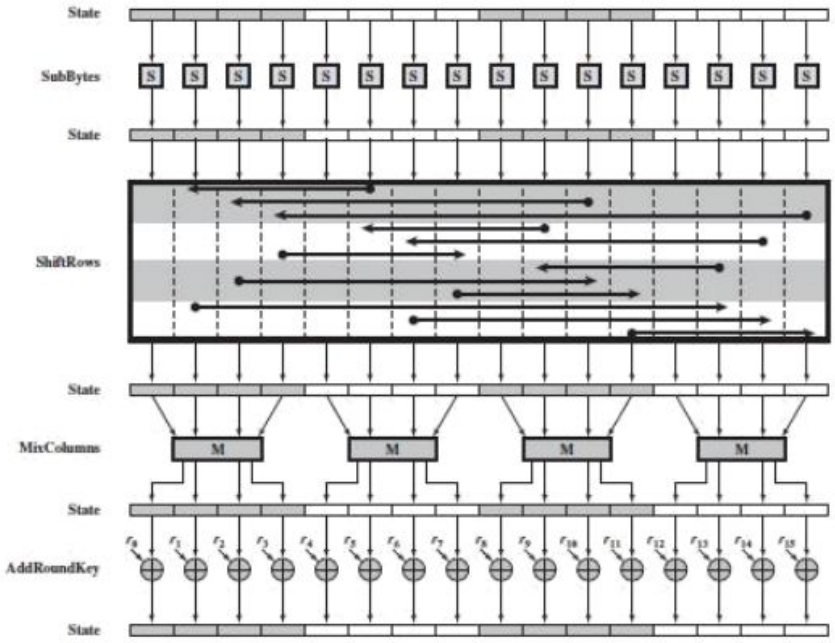
4. The structure is quite simple. For both encryption and decryption, the cipher begins with an AddRoundKey stage, followed by nine rounds that each includes all four stages, followed by a tenth round of three stages.

5. Only the AddRoundKey stage makes use of the key.

6. The AddRoundKey stage is, in effect, a form of Vernam cipher and by itself would not be formidable.

7. Each stage is easily reversible. For the Substitute Byte, ShiftRows, and MixColumns stages, an inverse function is used in the decryption algorithm. For the AddRoundKey stage, the inverse is achieved by XORing the same round key to the block, using the result that $A \oplus B \oplus B = A$.

8. As with most block ciphers, the decryption algorithm makes use of the expanded key in reverse order. However, the decryption algorithm is not



identical to the encryption algorithm. This is a consequence of the particular structure of AES.

9. Once it is established that all four stages are reversible, it is easy to verify that decryption does recover the plaintext. Figure 5.3 lays out encryption and decryption going in opposite vertical directions. At each horizontal point (e.g., the dashed line in the figure), State is the same for both encryption and decryption.

10. The final round of both encryption and decryption consists of only three stages. Again, this is a consequence of the particular structure of AES and is required to make the cipher reversible.

Inner Workings of a Round

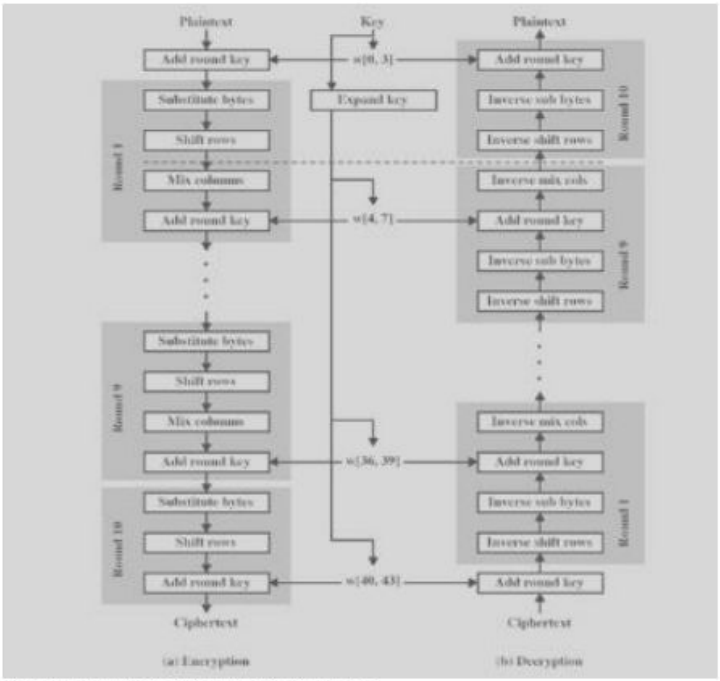
The algorithm begins with an Add round key stage followed by 9 rounds of four stages and a tenth round of three stages. This applies for both encryption and decryption with the exception that each stage of a round the decryption algorithm is the inverse of it's counterpart in the encryption algorithm. The four stages are as follows:

1. Substitute bytes
2. Shift rows
3. Mix Columns
4. Add Round Key

The tenth round simply leaves out the Mix Columns stage. The first nine rounds of the decryption algorithm consist of the following:

1. Inverse Shift rows
2. Inverse Substitute bytes
3. Inverse Add Round Key
4. Inverse Mix Columns

Again, the tenth round simply leaves out the Inverse Mix Columns stage. Each of these stages will now be considered in more detail.



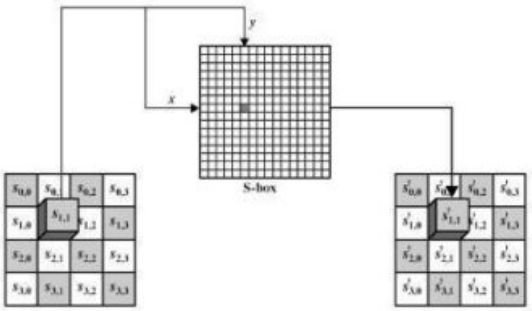
Overall structure of the AES algorithm.

AES transformation functions

Substitute Bytes

This stage (known as SubBytes) is simply a table lookup using a16×16 matrix of byte values called an s-box. This matrix consists of all the possible combinations of an 8 bit sequence ($2^8 = 16 \times 16 = 256$). However, the s-box is not just a random permutation of these values and there is a well defined method for creating the s-box tables. The designers of Rijndael showed how this was done unlike the s-boxes in DES for which no rationale was given. We will not be too concerned here how the s-boxes are made up and can simply take them as table lookups.

Again the matrix that gets operated upon throughout the encryption is known as state. We will be concerned with how this matrix is effected in each round. For this particular



(a) S-box

	y															
	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
0	63	7C	77	7B	F2	6B	6F	C5	30	01	67	2B	FE	D7	AB	76
1	CA	82	C9	7D	FA	59	47	F0	AD	D4	A2	AF	9C	A4	72	C0
2	B7	FD	93	26	36	3F	F7	CC	34	A5	E5	F1	71	D8	31	15
3	04	C7	23	C3	18	96	05	9A	07	12	80	E2	EB	27	B2	75
4	09	83	2C	1A	1B	6E	5A	A0	52	3B	D6	B3	29	E3	2F	84
5	53	D1	00	ED	20	FC	B1	5B	6A	CB	BE	39	4A	4C	58	CF
6	D0	EF	AA	FB	43	4D	33	85	45	F9	02	7F	50	3C	9F	A8
7	51	A3	40	8F	92	9D	38	F5	BC	B6	DA	21	10	FF	F3	D2
8	CD	0C	13	EC	5F	97	44	17	C4	A7	7E	3D	64	5D	19	73
9	60	81	4F	DC	22	2A	90	88	46	EE	B8	14	DE	5E	0B	DB
A	E0	32	3A	0A	49	06	24	5C	C2	D3	AC	62	91	95	E4	79
B	E7	C8	37	6D	8D	D5	4E	A9	6C	56	F4	EA	65	7A	AE	08
C	BA	78	25	2E	1C	A6	B4	C6	E8	DD	74	1F	4B	BD	8B	8A
D	70	3E	B5	66	48	03	F6	0E	61	35	57	B9	86	C1	1D	9E
E	E1	F8	98	11	69	D9	8E	94	9B	1E	87	E9	CE	55	28	DF
F	8C	A1	89	0D	BF	E6	42	68	41	99	2D	0F	B0	54	BB	16

(b) Inverse S-box

	y															
	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
0	52	09	6A	D5	30	36	A5	38	BF	40	A3	9E	81	F3	D7	FB
1	7C	E3	39	82	9B	2F	FF	87	34	8E	43	44	C4	DE	E9	CB
2	54	7B	94	32	A6	C2	23	3D	EE	4C	95	0B	42	FA	C3	4E
3	08	2E	A1	66	28	D9	24	B2	76	5B	A2	49	6D	8B	D1	25
4	72	F8	F6	64	86	68	98	16	D4	A4	5C	CC	5D	65	B6	92
5	6C	70	48	50	FD	ED	B9	DA	5E	15	46	57	A7	8D	9D	84
6	90	D8	AB	00	8C	BC	D3	0A	F7	E4	58	05	B8	B3	45	06
7	D0	2C	1E	8F	CA	3F	0F	02	C1	AF	BD	03	01	13	8A	6B
8	3A	91	11	41	4F	67	DC	EA	97	F2	CF	CE	F0	B4	E6	73
9	96	AC	74	22	E7	AD	35	85	E2	F9	37	E8	1C	75	DF	6E
A	47	F1	1A	71	1D	29	C5	89	6F	B7	62	0E	AA	18	BE	1B
B	FC	56	3E	4B	C6	D2	79	20	9A	DB	C0	FE	78	CD	5A	F4
C	1F	DD	A8	33	88	07	C7	31	B1	12	10	59	27	80	EC	5F
D	60	51	7F	A9	19	B5	4A	0D	2D	E5	7A	9F	93	C9	9C	EF
E	A0	E0	3B	4D	AE	2A	F5	B0	C8	EB	BB	3C	83	53	99	61
F	17	2B	04	7E	BA	77	D6	26	E1	69	14	63	55	21	0C	7D

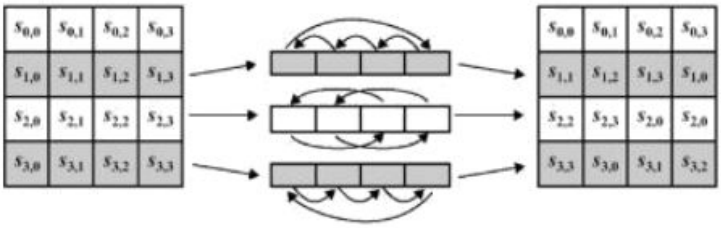
round each byte is mapped into a new byte in the following way: the leftmost nibble of the byte is used to specify a particular row of the s-box and the rightmost nibble specifies a column. For example, the byte {95} (curly brackets represent hex values in FIPS PUB 197) selects row 9 column 5 which turns out to contain the value {2A}. This is then used to update the state matrix.

The Inverse substitute byte transformation (known as InvSubBytes) makes use of an inverse s-box. In this case what is desired is to select the value {2A} and get the value {95}. Shows the two s-boxes and it can be verified that this is in fact the case.

The s-box is designed to be resistant to known cryptanalytic attacks. Specifically, the Rijndael developers sought a design that has a low correlation between input bits and output bits, and the property that the output cannot be described as a simple mathematical function of the input. In addition, the s-box has no fixed points (s-box (a) = a) and no opposite fixed points (s-box(a) =a) where a is the bitwise compliment of a. The s-box must be invertible if decryption is to be possible (Is-box[s-ox(a)]=a) however it should not be its self inverse i.e. s-box (a)=Is-box(a)

Shift Row Transformation

- The first row of state is not altered.
- The second row is shifted 1 bytes to the left in a circular manner.
- The third row is shifted 2 bytes to the left in a circular manner.
- The fourth row is shifted 3 bytes to the left in a circular manner.



The Inverse Shift Rows transformation (known as InvShiftRows) performs these circular shifts in the opposite direction for each of the last three rows (the first row was unaltered to begin with).

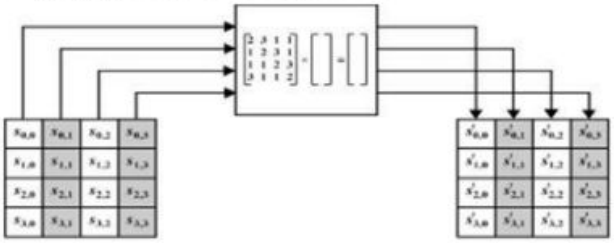
This operation may not appear to do much but if you think about how the bytes are ordered within state then it can be seen to have far more of an impact. Remember that state is treated as an array of four byte columns, i.e. the first column actually represents bytes 1 ,2 ,3 and 4. A one byte shift is herefore a linear distance of four bytes. The transformation also ensures that the four bytes of one column are spread out to four different columns.

Mix Column Transformation

This stage (known as MixColumn) is basically a substitution but it makes use of arithmetic of GF(2^8). Each column is operated on individually. Each byte of a column is mapped into a new value that is a function of all four bytes in the column. The transformation can be determined by the following matrix multiplication on state.

$$\begin{bmatrix} 02 & 03 & 01 & 01 \\ 01 & 02 & 03 & 01 \\ 01 & 01 & 02 & 03 \\ 03 & 01 & 01 & 02 \end{bmatrix} \begin{bmatrix} s_{0,0} & s_{0,1} & s_{0,2} & s_{0,3} \\ s_{1,0} & s_{1,1} & s_{1,2} & s_{1,3} \\ s_{2,0} & s_{2,1} & s_{2,2} & s_{2,3} \\ s_{3,0} & s_{3,1} & s_{3,2} & s_{3,3} \end{bmatrix} = \begin{bmatrix} s'_{0,0} & s'_{0,1} & s'_{0,2} & s'_{0,3} \\ s'_{1,0} & s'_{1,1} & s'_{1,2} & s'_{1,3} \\ s'_{2,0} & s'_{2,1} & s'_{2,2} & s'_{2,3} \\ s'_{3,0} & s'_{3,1} & s'_{3,2} & s'_{3,3} \end{bmatrix}$$

Each element of the product matrix is the sum of products of elements of one row and one column. In this case the individual additions and multiplications are performed in GF (2^8) . The MixColumns transformation of a single column j($0 \le j \le 3$)of state can be expressed as



$$s'_{0,j} = (2 \cdot s_{0,j}) \oplus (3 \cdot s_{1,j}) \oplus s_{2,j} \oplus s_{3,j}$$
$$s'_{1,j} = s_{0,j} \oplus (2 \cdot s_{1,j}) \oplus (3 \cdot s_{2,j}) \oplus s_{3,j}$$
$$s'_{2,j} = s_{0,j} \oplus s_{1,j} \oplus (2 \cdot s_{2,j}) \oplus (3 \cdot s_{3,j})$$
$$s'_{3,j} = (3 \cdot s_{0,j}) \oplus s_{1,j} \oplus s_{2,j} \oplus (2 \cdot s_{3,j})$$

The following is an example of MixColumns:

87	F2	4D	97
6E	4C	90	EC
46	E7	4A	C3
A6	8C	D8	95

→

47	40	A3	4C
37	D4	70	9F
94	E4	3A	42
ED	A5	A6	BC

In particular, multiplication of a value by (i.e., by {02}) can be implemented as a 1-bit left shift followed by a conditional bitwise XOR with (0001 1011) if the leftmost bit of the original value (prior to the shift) is 1. In multiplication left most bit value is 0 only perform the left shift operation.

$$\begin{aligned}
(\{02\} \cdot \{87\}) \oplus (\{03\} \cdot \{6E\}) \oplus \{46\} \oplus \{A6\} &= \{47\} \\
\{87\} \oplus (\{02\} \cdot \{6E\}) \oplus (\{03\} \cdot \{46\}) \oplus \{A6\} &= \{37\} \\
\{87\} \oplus \{6E\} \oplus (\{02\} \cdot \{46\}) \oplus (\{03\} \cdot \{A6\}) &= \{94\} \\
(\{03\} \cdot \{87\}) \oplus \{6E\} \oplus \{46\} \oplus (\{02\} \cdot \{A6\}) &= \{ED\}
\end{aligned}$$

For the first equation, we have $\{02\} \cdot \{87\} = (0000\ 1110) \oplus (0001\ 1011) = (0001\ 0101)$ and $\{03\} \cdot \{6E\} = \{6E\} \oplus (\{02\} \cdot \{6E\}) = (0110\ 1110) \oplus (1101\ 1100) = (1011\ 0010)$. Then,

$$\begin{aligned}
\{02\} \cdot \{87\} &= 0001\ 0101 \\
\{03\} \cdot \{6E\} &= 1011\ 0010 \\
\{46\} &= 0100\ 0110 \\
\{A6\} &= \underline{1010\ 0110} \\
&\quad 0100\ 0111 = \{47\}
\end{aligned}$$

The other equations can be similarly verified.

Add round key transformation:

In this stage (known as AddRoundKey) the 128 bits of state are bitwise XORed with the 128 bits of the round key. The operation is viewed as a columnwise operation between the 4 bytes of a state column and one word of the round key. This transformation is as simple as possible which helps in efficiency but it also effects every bit of state .

47	40	A3	4C
37	D4	70	9F
94	E4	3A	42
ED	A5	A6	BC

⊕

AC	19	28	57
77	FA	D1	5C
66	DC	29	00
F3	21	41	6A

=

EB	59	8B	1B
40	2E	A1	C3
F2	38	13	42
1E	84	E7	D6

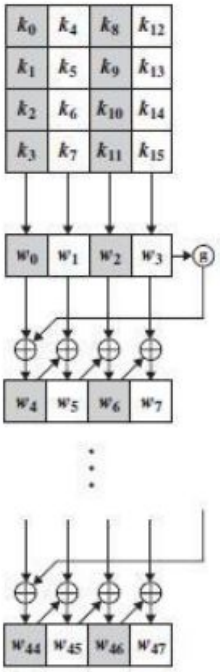
The first matrix is **State**, and the second matrix is the round key.

The **inverse add round key transformation** is identical to the forward add round key transformation, because the XOR operation is its own inverse

AES key Expansion:

Key Expansion Algorithm

The AES key expansion algorithm takes as input a four-word (16-byte) key and produces a linear array of 44 words (176 bytes).This is sufficient to provide a four-word round key for the initial AddRoundKey stage and each of the 10 rounds of the cipher



1. RotWord performs a one-byte circular left shift on a word.This means that an input word [B_0, B_1, B_2, B_3] is transformed into [B_1, B_2, B_3, B_0].
2. SubWord performs a byte substitution on each byte of its input word, using the S-box .

3. The result of steps 1 and 2 is XORed with a round constant, Rcon[j].

The round constant is a word in which the three rightmost bytes are always 0. Thus, the effect of an XOR of a word with Rcon is to only perform an XOR on the leftmost byte of the word.The round constant is different for each round and is defined as Rcon[j] = (RC[j], 0, 0, 0) with RC[1] = 1 RC[j] = 2 *RC[j-1] and with multiplication defined over the field GF(2^8).The values of RC[j] in hexadecimal are

Multiple encryption and Triple DES:

- Multiple encryption is a technique in which an encryption algorithm is used multiple times. In the first instance, plaintext is converted to ciphertext using the encryption algorithm. This ciphertext is then used as input and the algorithm is applied again. This process may be repeated through any number of stages.
- Triple DES makes use of three stages of the DES algorithm, using a total of two or three distinct keys.

Double DES

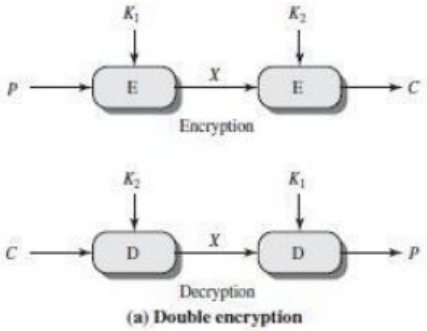
- The simplest form of multiple encryption has two encryption stages and two keys. Given a plaintext *P* and two encryption keys k_1 and k_2 , ciphertext C is generated as

$$C = E(K_2, E(K_1, P))$$

Decryption requires that the keys be applied in reverse order:

$$P = D(K_1, D(K_2, C))$$

For DES, this scheme apparently involves a key length of 56 * 2 = 112 bits, resulting in a dramatic increase in cryptographic strength. But we need to examine the algorithm more closely.



(a) Double encryption

MEET-IN-THE-MIDDLE ATTACK

The algorithm, known as a **meet-in-the-middle attack**, was first described in [DIFF77]. It is based on the observation that, if we have

$$C = E(K_2, E(K_1, P))$$

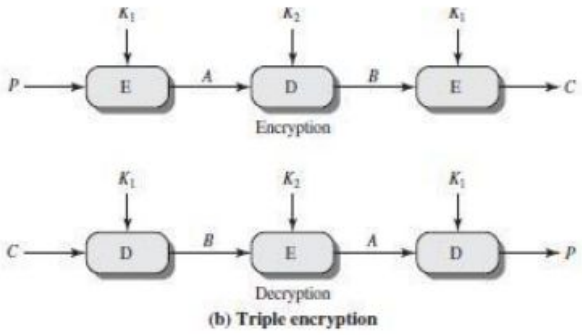
then (see Figure)

$$X = E(K_1, P) = D(K_2, C)$$

Given a known pair, (P, C) , the attack proceeds as follows. First, encrypt P for all possible 2^{56} values of k_1. Store these results in a table and then sort the table by the values of x. Next, decrypt C using all 2^{56} possible values of k_2 . As each decryption is produced, check the result against the table for a match. If a match occurs, then test the two resulting keys against a new known plaintext–ciphertext pair. If the two keys produce the correct ciphertext, accept them as the correct keys.

Triple DES with two keys

triple encryption method that uses only two keys [TUCH79]. The function follows an encrypt-decrypt-encrypt (EDE) sequence.



(b) Triple encryption

$$C = E(K_1, D(K_2, E(K_1, P)))$$

$$P = D(K_1, E(K_2, D(K_1, C)))$$

3DES with two keys is a relatively popular alternative to DES.

Currently, there are no practical cryptanalytic attacks on 3DES.

It is worth looking at several proposed attacks on 3DES that

A known-plaintext attack:

1. Obtain pairs n(p,c). This is the known plaintext. Place these in a table (Table 1)

sorted on the values of (Figure 6.2b).

2. Pick an arbitrary value a for A, and create a second table (Figure 6.2c) with entries defined in the following fashion. For each of the 2^{56} possible keys , $k_1=i$ calculate the plaintext value P_i that produces :

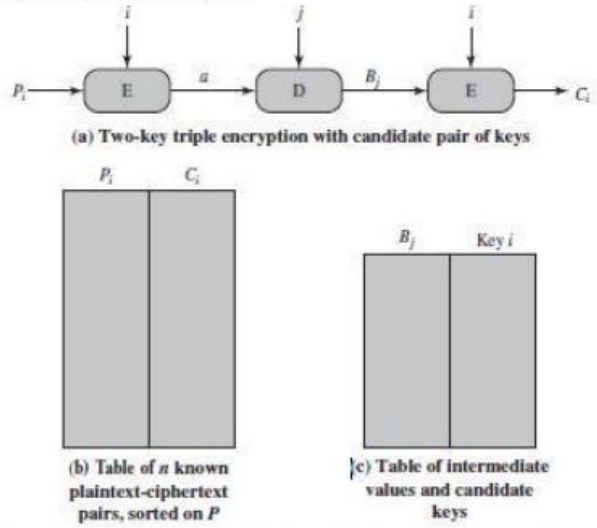
   $Pi = D(i, a)$

For each P_i that matches an entry in Table 1, create an entry in Table 2 consisting of

the k_1 value and the value of B that is produced for the (P,C) pair from Table 1, assuming that value of k_1 :

$$B = D(i, C)$$

At the end of this step, sort Table 2 on the values of *B*.



(a) Two-key triple encryption with candidate pair of keys

(b) Table of *n* known plaintext-ciphertext pairs, sorted on *P*

(c) Table of intermediate values and candidate keys

3. We now have a number of candidate values of k_1 in Table 2 and are in a position to search for a value of k_2 . For each of the 2^{56} possible keys $k_2=j$, calculate the second intermediate value for our chosen value of a:

   $$B_j = D(j, a)$$

   At each step, look up B_j in Table 2. If there is a match, then the corresponding key i from Table 2 plus this value of *j* are candidate values for the unknown keys (k_1,k_2). Why? Because we have found a pair of keys (I,j) that produce a known (P,C) pair (Figure 6.2a).

4. Test each candidate pair of keys(i,j) on a few other plaintext–ciphertext pairs. If a pair of keys produces the desired ciphertext, the task is complete. If no pair succeeds, repeat from step 1 with a new value of a .

Triple DES with Three Keys

Although the attacks just described appear impractical, anyone using two-key 3DES may feel some concern.Thus, many researchers now feel that three-key 3DES is the preferred alternative (e.g., [KALI96a]).Three-key 3DES has an effective key length of 168 bits and is defined as

$$C = E(K_3, D(K_2, E(K_1, P)))$$

Backward compatibility with DES is provided by putting $k_3=k_2$ or $k_1=k_2$.

BLOCK CIPHER MODES OF OPERATION

Four DES modes of operations have been defined (FIPS 81, http://www.itl.nist.gov/fipspubs/fip81.htm):

Mode	Description	Typical application
Electronic Codebook (ECB)	Each block of 64 plaintext bits is encoded independently using the same key	Secure transmission of single values (e.g., an encryption key)
Cipher Block Chaining (CBC)	The input to the encryption algorithm is the XOR of the next 64 bits of the plaintext and the preceding 64 bits of the ciphertext	General-purpose block-oriented transmission Authentication
Cipher Feedback (CFB)	Input is processed s bits at a time. Preceding ciphertext is used as input to the encryption algorithm to produce pseudorandom output, which is XORed with plaintext to produce next unit of ciphertext	General-purpose stream-oriented transmission Authentication
Output Feedback (OFB)	Similar to CFB, except that the input to the encryption algorithm is the preceding DES output	Stream-oriented transmission over noisy channel (e.g., satellite communication)
Counter (CTR)	Each block of plaintext is XORed with an encrypted counter. The counter is incremented for each subsequent block	General-purpose block-oriented transmission Useful for high-speed requirements

ELECTRONIC CODEBOOK MODE

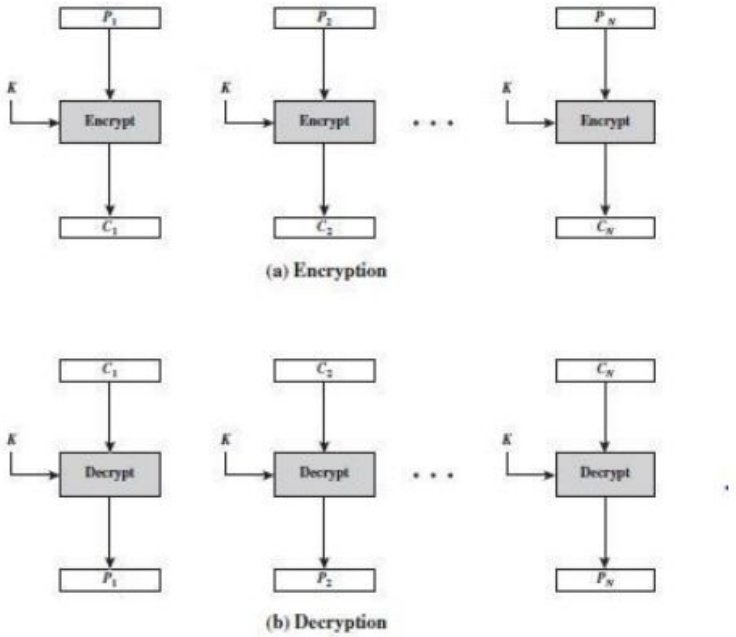
The simplest mode is the **electronic codebook** (**ECB**) mode, in which plaintext is handled one block at a time and each block of plaintext is encrypted using the same key. The term *codebook* is used because, for a given key, there is a unique ciphertext for every -bit block of plaintext.

For a message longer than bits, the procedure is simply to break the message into b-bit blocks, padding the last block if necessary. Decryption is performed one block at a time, always using the same key the plaintext (padded as necessary) consists of a sequence of *b*-bit blocks, *P*1, *P*2, …, *PN*; the corresponding sequence of ciphertext blocks is *C*1, *C*2, .., *CN*.

The ECB method is ideal for a short amount of data, such as an encryption key. Thus, if you want to transmit a DES or AES key securely, ECB is the appropriate mode to use.

The most significant characteristic of ECB is that if the same b-bit block of plaintext appears more than once in the message, it always produces the same ciphertext.

For lengthy messages, the ECB mode may not be secure.



(a) Encryption

(b) Decryption

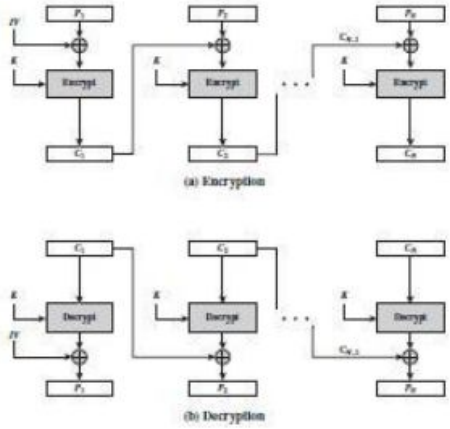
CIPHER BLOCK CHAINING MODE

To overcome the security deficiencies of ECB, we would like a technique in which the same plaintext block, if repeated, produces different ciphertext blocks.A simple way to satisfy this requirement is the **cipher block chaining** (**CBC**) mode.

The input to the encryption algorithm is the XOR of the current plaintext block and the preceding ciphertext block; the same key is used for each block. In effect, we have chained together the processing of the sequence of plaintext blocks. The input to the encryption function for each plaintext block bears no fixed relationship to the plaintext block. Therefore, repeating patterns of bits are not exposed.

For decryption, each cipher block is passed through the decryption algorithm. The result is XORed with the preceding ciphertext block to produce the plaintext block. To see that this works, we can write

$$C_j = \mathsf{E}(K, [C_{j-1} \_ P_j])$$



$$\mathsf{D}(K, C_j) = \mathsf{D}(K, E(K, [C_{j-1} \_ P_j]))$$

$$\mathsf{D}(K, C_j) = C_{j-1} \_ P_j$$

$$C_{j-1} \_ \mathsf{D}(K, C_j) = C_{j-1} \_ C_{j-1} \_ P_j = P_j$$

To produce the first block of ciphertext, an initialization vector (IV) is XORed with the first block of plaintext. On decryption, the IV is XORed with the output of the decryption algorithm to recover the first block of plaintext. The IV is a data block that is that same size as the cipher block.

The IV must be known to both the sender and receiver but be unpredictable by a third party. In particular, for any given plaintext, it must not be possible to predict the IV that will be associated to the plaintext in advance of the generation of the IV. For maximum security, the IV should be protected against unauthorized changes. This could be done by sending the IV using ECB encryption. One reason for protecting the IV is as follows: If an opponent is able to fool the receiver into using a different value for IV, then the opponent is able to invert selected bits in the first block of plaintext.To see this, consider

$C_1 = \mathsf{E}(K, [\mathsf{IV} \_ P_1])$

$P_1 = \mathsf{IV} \_ \mathsf{D}(K, C_1)$

CIPHER FEEDBACK MODE

DES is a block cipher, but it may be used as a stream cipher if to use the Cipher Feedback Mode (CFB) or the Output Feedback Mode (OFB). A stream cipher eliminates the need to pad a message to be an integral number of blocks. It also can operate in real time. Thus, if a character stream is being transmitted, each character can be encrypted and transmitted immediately using a character-oriented stream cipher.

CFB scheme follows:

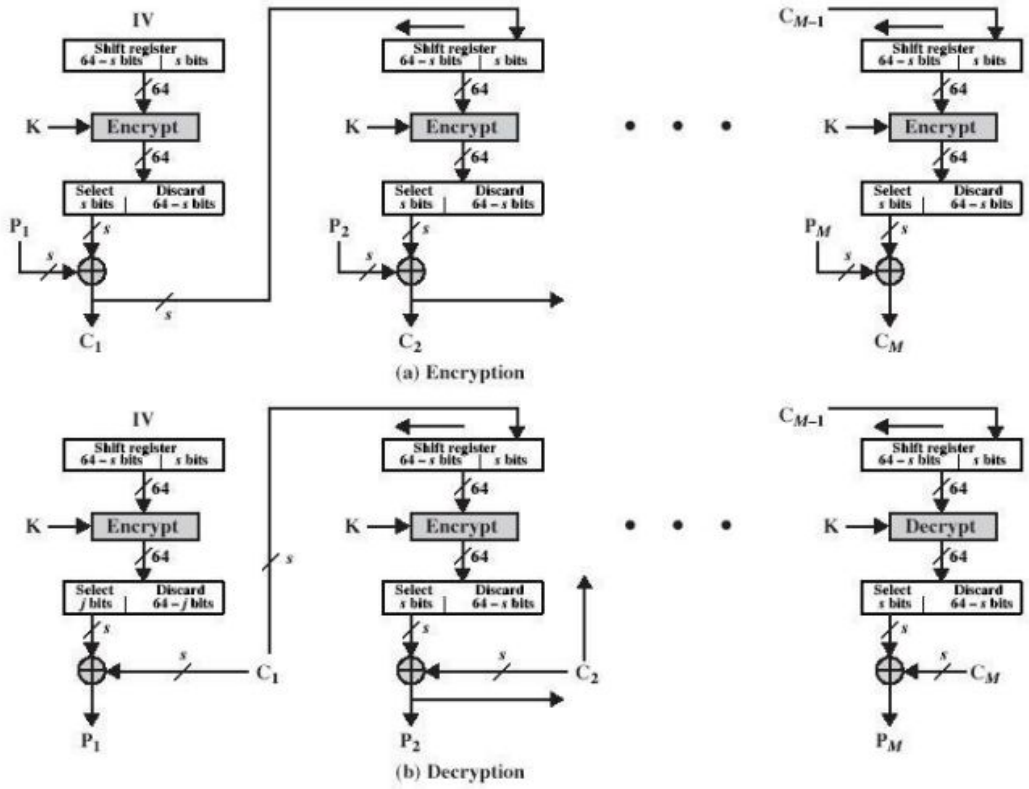


Figure 3.13 *s*-bit Cipher Feedback (CFB) Mode

In Fig. 3.13, it is assumed that the unit of transmission is s bits; usually, s=8. As with CBC, the units of plaintext are chained together, so that the ciphertext of any plaintext unit is a function of all the preceding plaintext. In this case, rather than units of 64 bits, the plaintext is divided into segments of s bits.

Consider encryption. The input to the encryption function is a 64-bit shift register that is initially set to some initialization vector (IV). The leftmost (most significant) s bits of the output of the encryption function are XORed with the first segment of plaintext P1 to produce the first unit of ciphertext C1, which is then transmitted. In addition, the contents of the shift register are shifted left by s bits and C1 is placed in the rightmost (least significant) s bits of the shift register. This process continues until all plaintext units have been encrypted.

For decryption, the same scheme is used except that the received ciphertext unit is XORed with the output of the encryption function to produce the plaintext unit.

OUTPUT FEEDBACK MODE

The Output Feedback Mode (OFB) is similar in structure to that of CFB:

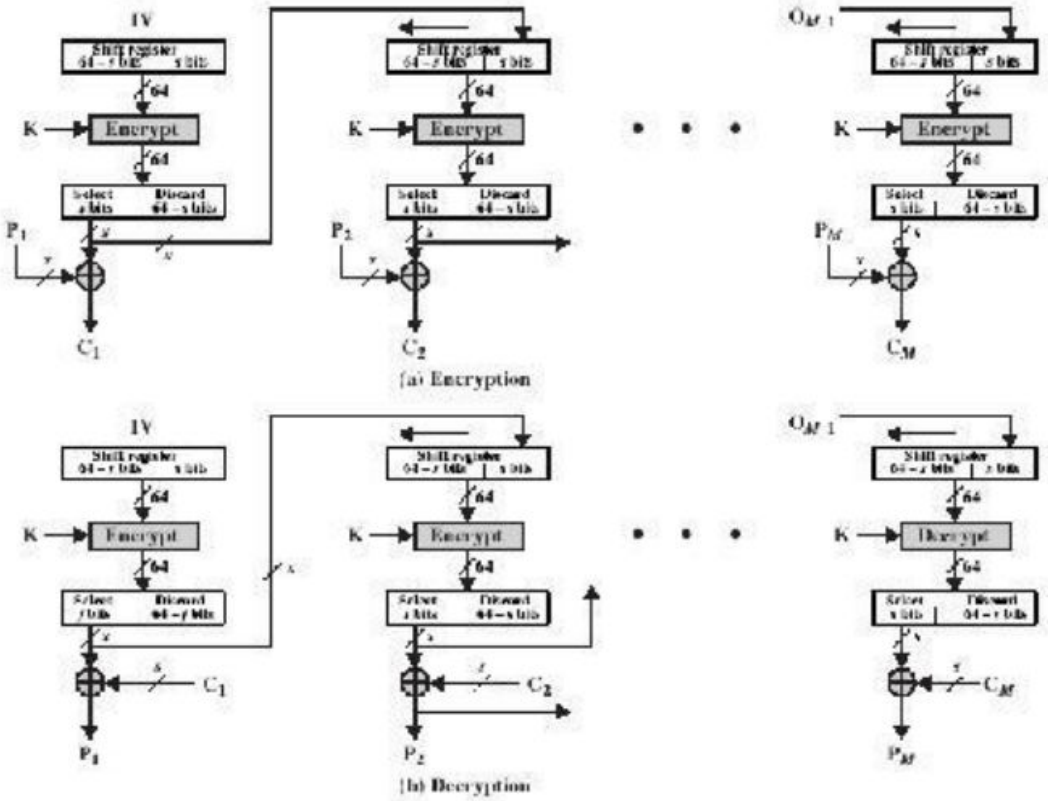


Figure 3.14 *s*-bit Output Feedback (OFB) Mode

As can be seen, it is the output of the encryption function that is fed back to the shift register in OFB, whereas in CFB the ciphertext unit is fed back to the shift register. One advantage of the OFB method is that bit errors in transmission do not propagate.

COUNTER MODE

A counter, equal to the plaintext block size is used. The only requirement stated in SP 800-38A NIST Special Publication 800 -38 A, 2001 Edition, Morris Dworkin, Recommendations for Block Cipher Modes of Operation) is that the counter value must be different for each plaintext block that is encrypted. This mode is with applications to ATM (asynchronous transfer mode) and IPsec (IP security) nowadays, but it was proposed in 1979.

Counter Mode works as follows:

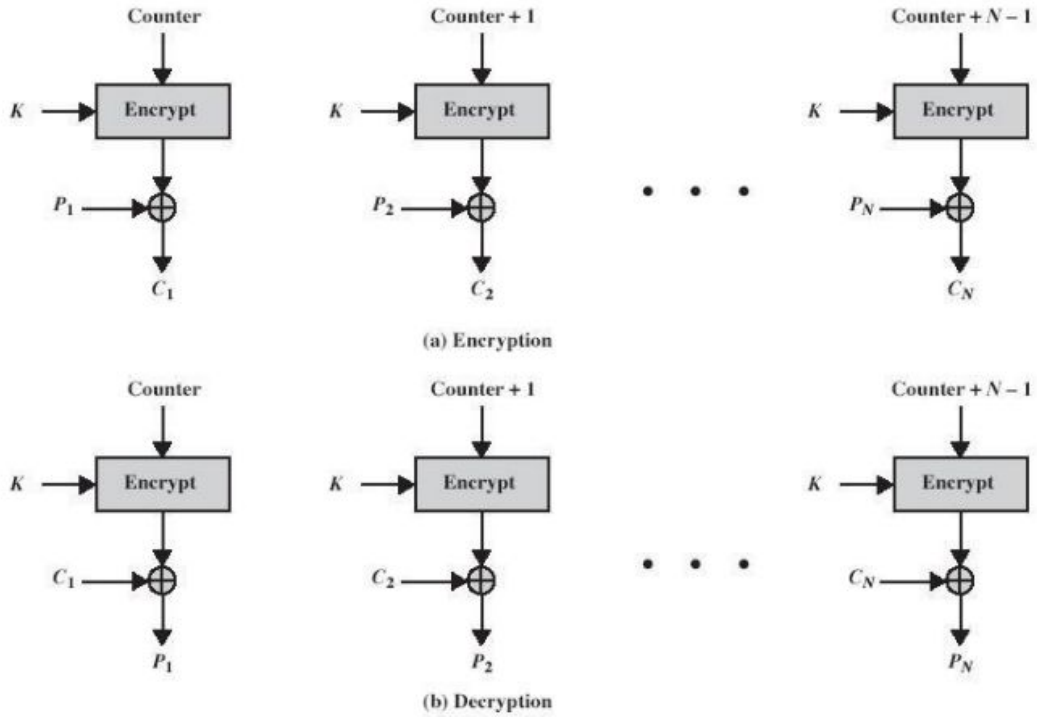


Figure 3.15 Counter (CTR) Mode

Addition is made modulo 2^b, where b is a block size. CTR mode is effective because blocks may be processed in parallel; encryption of keys may be made in advance, and only XOR will be made on-line; only necessary blocks may be decrypted; provides not less security than chaining modes but significantly simpler.