CRYPTOGRAPHY

The art and science of concealing the messages

to introduce secrecy in information security is

recognized as cryptography.

The word ‘cryptography’ was coined by combining two Greek words, ‘Krypto’ meaning hidden and ‘graphene’ meaning writing.

History of Cryptography

The art of cryptography is considered to be born along with the art of writing.

As civilizations evolved, human beings got organized in tribes, groups, and kingdoms.

This led to the emergence of ideas such as power, battles, supremacy, and politics.

These ideas further fueled the natural need of people to communicate secretly

with selective recipient which in turn ensured the continuous evolution of cryptography as well.

The roots of cryptography are found in Roman and Egyptian civilizations.

Hieroglyph − The Oldest Cryptographic Technique

The first known evidence of cryptography can be traced to the use of 'hieroglyph'. Some 4000 years ago, the Egyptians used to communicate by messages written in hieroglyph. This code was the secret known only to the scribes who used to transmit messages on behalf of the kings. One such hieroglyph is shown below.

Later, the scholars moved on to using simple mono-alphabetic substitution ciphers during 500 to 600 BC. This involved replacing alphabets of message with other alphabets with some secret rule. This **rule** became a **key** to retrieve the message back from the garbled message.

The earlier Roman method of cryptography, popularly known as the **Caesar Shift Cipher,** relies on shifting the letters of a message by an agreed number *threewasacommonchoice*, the recipient of this message would then shift the letters back by the same number and obtain the original message.

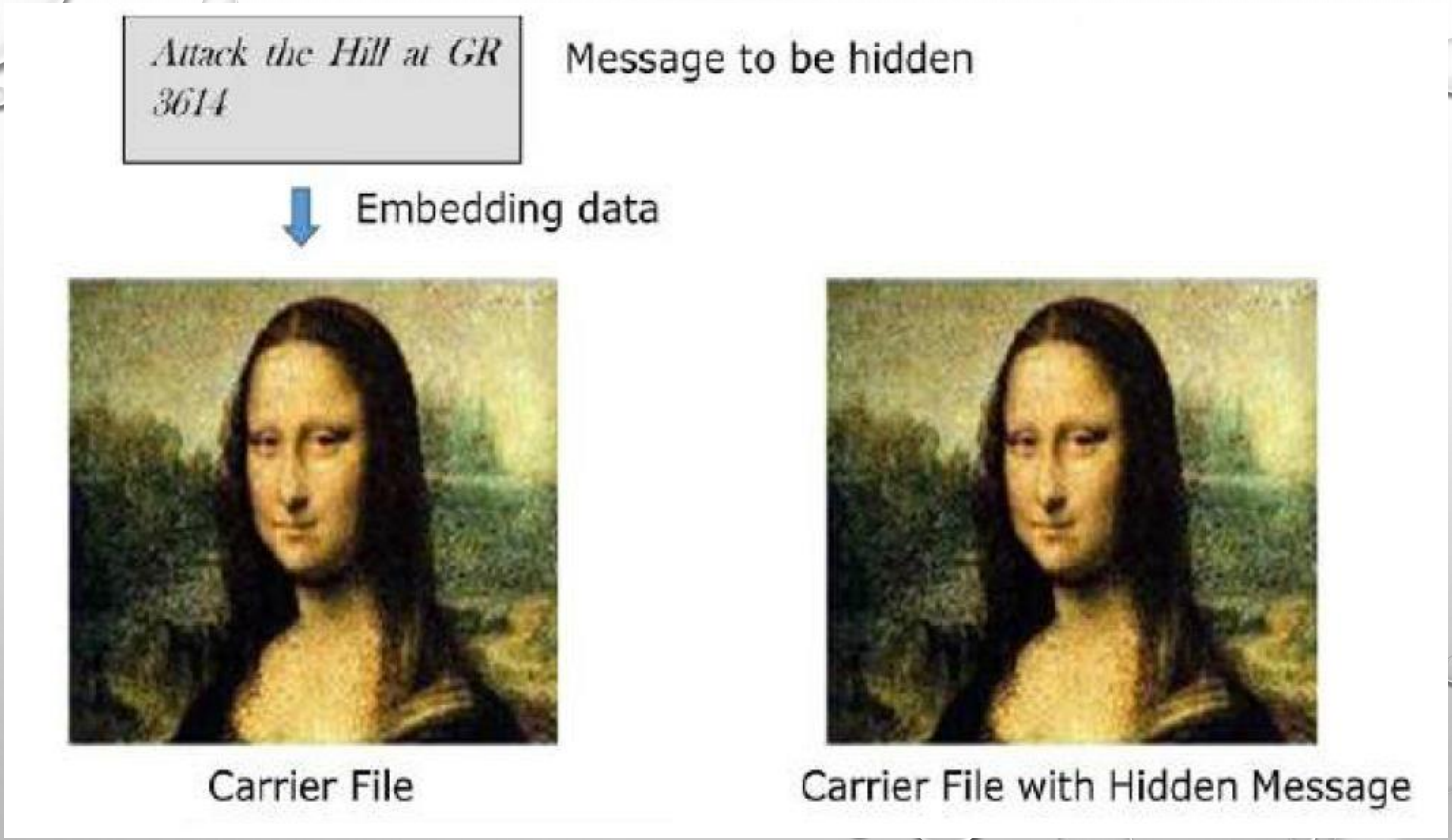
Steganography

Steganography is similar but adds another dimension to Cryptography.

In this method, people not only want to protect the secrecy of an information by concealing it, but they also want to make sure any unauthorized person gets no evidence that the information even exists.

For example, **invisible watermarking**.

In steganography, an unintended recipient or an intruder is unaware of the fact that observed data contains hidden information. In cryptography, an intruder is normally aware that data is being communicated, because they can see the coded/scrambled message.


Attack the Hill at GR 3614
Message to be hidden
Embedding data
Carrier File
Carrier File with Hidden Message

Evolution of Cryptography

- Improved coding techniques such as **Vigenere Coding** came into existence in the 15th century, which offered moving letters in the message with a number of variable places instead of moving them the same number of places.

- Only after the 19th century, cryptography evolved from the ad hoc approaches to encryption to the more sophisticated art and science of information security.

- In the early 20th century, the invention of mechanical and electromechanical machines, such as the **Enigma rotor machine,** provided more advanced and efficient means of coding the information.

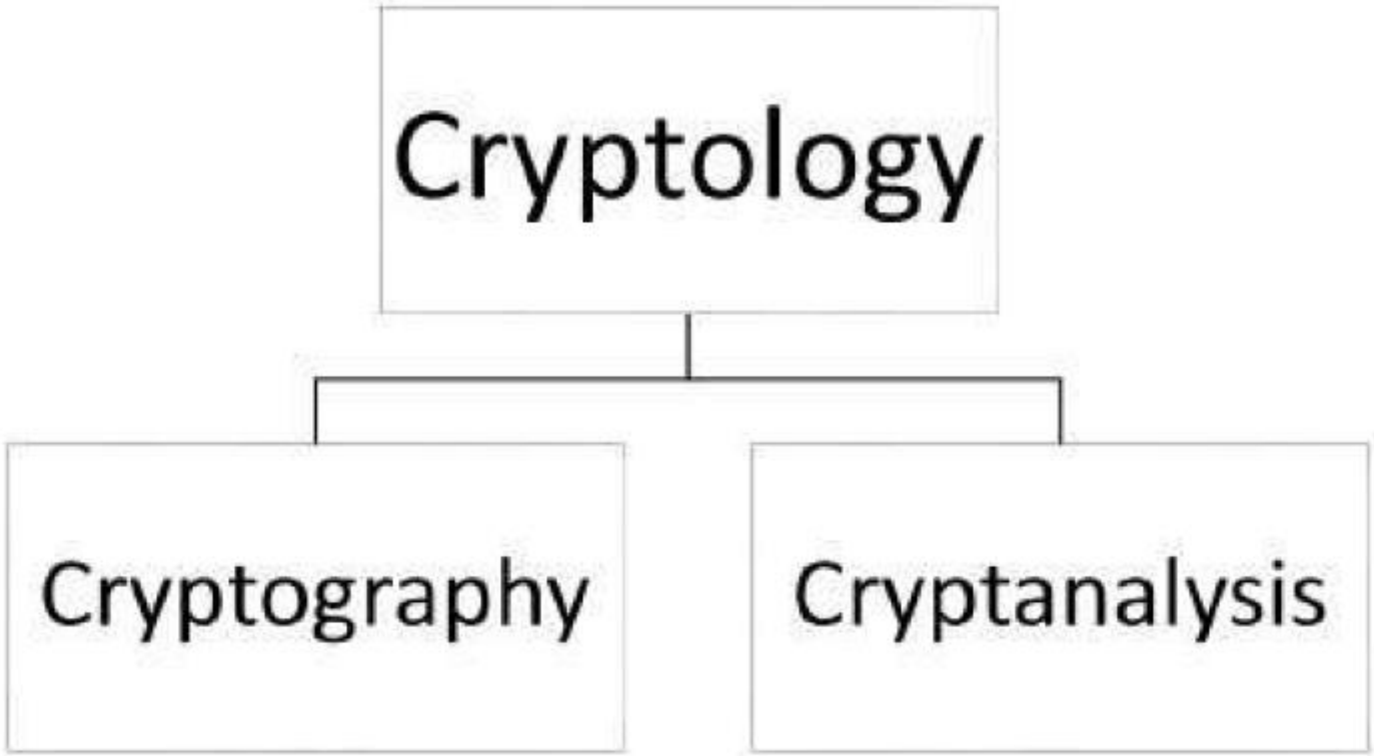
- During the period of World War II, both **cryptography** and **cryptanalysis** became excessively mathematical.

Classic Cryptography	Modern Cryptography
It manipulates traditional characters, i.e., letters and digits directly.	It operates on binary bit sequences.
It is mainly based on 'security through obscurity'. The techniques employed for coding were kept secret and only the parties involved in communication knew about them.	It relies on publicly known mathematical algorithms for coding the information. Secrecy is obtained through a secrete key which is used as the seed for the algorithms. The computational difficulty of algorithms, absence of secret key, etc., make it impossible for an attacker to obtain the original information even if he knows the algorithm used for coding.
It requires the entire cryptosystem for communicating confidentially.	Modern cryptography requires parties interested in secure communication to possess the secret key only.

Context of Cryptography

Cryptology, the study of cryptosystems, can be subdivided into two branches –

- Cryptography
- Cryptanalysis



What is Cryptography?

Cryptography is the art and science of making a cryptosystem that is capable of providing information security.

Cryptography deals with the actual securing of digital data.

It refers to the design of mechanisms based on mathematical algorithms that provide fundamental information security services.

What is Cryptanalysis?

The art and science of breaking the cipher text is known as cryptanalysis.

Cryptanalysis is the sister branch of cryptography and they both co-exist.

The cryptographic process results in the cipher text for transmission or storage. It involves the study of cryptographic mechanism with the intention to break them. Cryptanalysis is also used during the design of the new cryptographic techniques to test their security strengths.

Cryptography concerns with the design of cryptosystems, while cryptanalysis studies the breaking of cryptosystems.

Security Services of Cryptography

The primary objective of using cryptography is to provide the following four fundamental information security services. Let us now see the possible goals intended to be fulfilled by cryptography.

Confidentiality

Confidentiality is the fundamental security service provided by cryptography. It is a security service that keeps the information from an unauthorized person. It is sometimes referred to as **privacy** or **secrecy**.

Confidentiality can be achieved through numerous means starting from physical securing to the use of mathematical algorithms for data encryption.

Data Integrity

It is security service that deals with identifying any alteration to the data. The data may get modified by an unauthorized entity intentionally or accidently. Integrity service confirms that whether data is intact or not since it was last created, transmitted, or stored by an authorized user.

Data integrity cannot prevent the alteration of data, but provides a means for detecting whether data has been manipulated in an unauthorized manner.

Authentication

Authentication provides the identification of the originator. It confirms to the receiver that the data received has been sent only by an identified and verified sender.

Authentication service has two variants −

- **Message authentication** identifies the originator of the message without any regard router or system that has sent the message.

- **Entity authentication** is assurance that data has been received from a specific entity, say a particular website.

Apart from the originator, authentication may also provide assurance about other parameters related to data such as the date and time of creation/transmission.

Non-repudiation

It is a security service that ensures that an entity cannot refuse the ownership of a previous commitment or an action. It is an assurance that the original creator of the data cannot deny the creation or transmission of the said data to a recipient or third party.

Non-repudiation is a property that is most desirable in situations where there are chances of a dispute over the exchange of data. For example, once an order is placed electronically, a purchaser cannot deny the purchase order, if non-repudiation service was enabled in this transaction.

Cryptography Primitives

Cryptography primitives are nothing but the tools and techniques in Cryptography that can be selectively used to provide a set of desired security services −

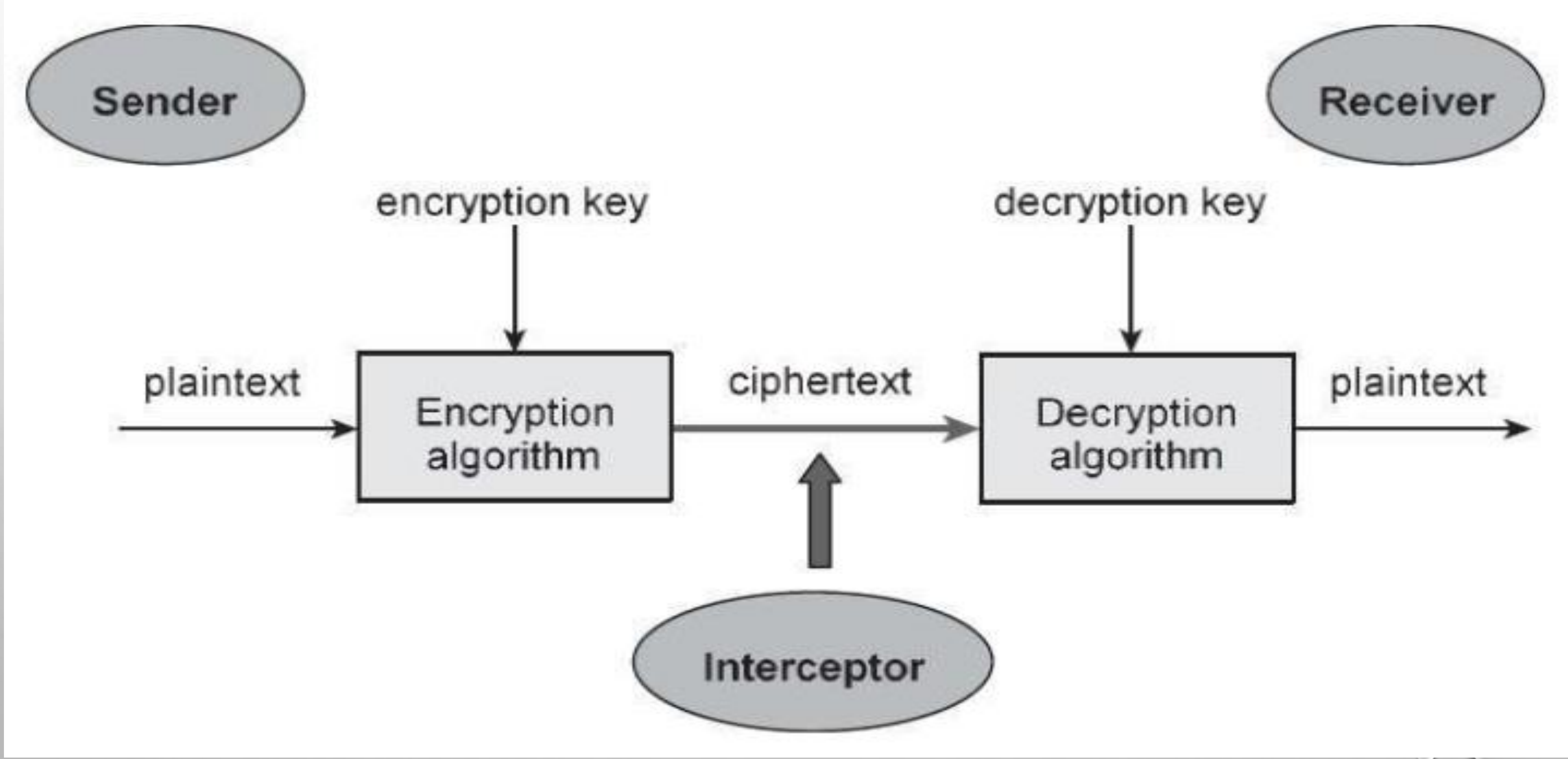
- Encryption
- Hash functions
- Message Authentication codes *MAC*
- Digital Signatures

The following table shows the primitives that can achieve a particular security service on their own.

Primitives → / Service ↓	Encryption	Hash Function	MAC	Digital Signature
Confidentiality	Yes	No	No	No
Integrity	No	Sometimes	Yes	Yes
Authentication	No	No	Yes	Yes
Non Reputation	No	No	Sometimes	Yes

CRYPTOSYSTEMS

A cryptosystem is an implementation of cryptographic techniques and their accompanying infrastructure to provide information security services. A cryptosystem is also referred to as a **cipher system**.



Components of a Cryptosystem

The various components of a basic cryptosystem are as follows −

- **Plaintext.** It is the data to be protected during transmission.
- **Encryption Algorithm.** It is a mathematical process that produces a ciphertext for any given plaintext and encryption key. It is a cryptographic algorithm that takes plaintext and an encryption key as input and produces a ciphertext.
- **Ciphertext.** It is the scrambled version of the plaintext produced by the encryption algorithm using a specific the encryption key. The ciphertext is not guarded. It flows on public channel. It can be intercepted or compromised by anyone who has access to the communication channel.
- **Decryption Algorithm,** It is a mathematical process, that produces a unique plaintext for any given ciphertext and decryption key. It is a cryptographic algorithm that takes a ciphertext and a decryption key as input, and outputs a plaintext. The decryption algorithm essentially reverses the encryption algorithm and is thus closely related to it.
- **Encryption Key.** It is a value that is known to the sender. The sender inputs the encryption key into the encryption algorithm along with the plaintext in order to compute the ciphertext.
- **Decryption Key.** It is a value that is known to the receiver. The decryption key is related to the encryption key, but is not always identical to it. The receiver inputs the decryption key into the decryption algorithm along with the ciphertext in order to compute the plaintext.

For a given cryptosystem, a collection of all possible decryption keys is called a **key space**.

An **interceptor** *an attacker* is an unauthorized entity who attempts to determine the plaintext.

He can see the ciphertext and may know the decryption algorithm. He, however, must never know the decryption key.

Types of Cryptosystems

Fundamentally, there are two types of cryptosystems based on the manner in which encryption- decryption is carried out in the system −

- Symmetric Key Encryption
- Asymmetric Key Encryption

The main difference between these cryptosystems is the relationship between the encryption and the decryption key.

Logically, in any cryptosystem, both the keys are closely associated.

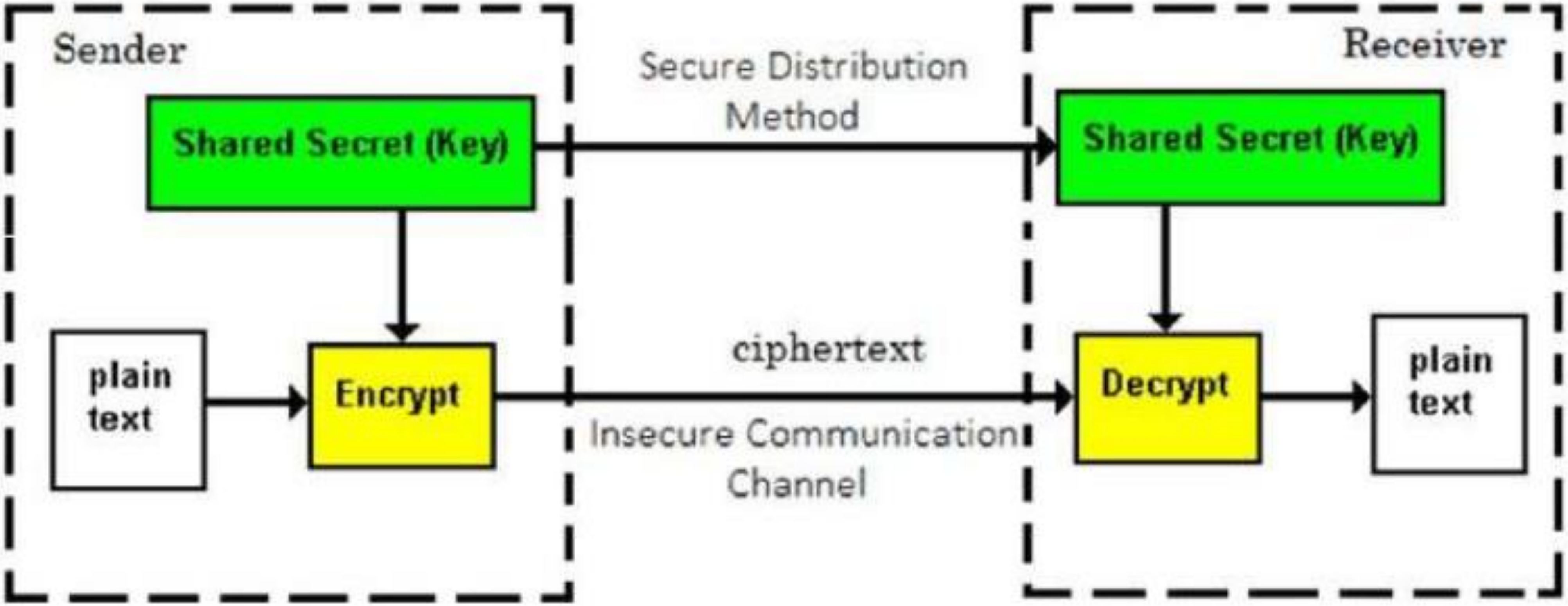
It is practically impossible to decrypt the ciphertext with the key that is unrelated to the encryption key.

Symmetric Key Encryption

The encryption process where **same keys are used for encrypting and decrypting** the information is known as Symmetric Key Encryption.

The study of symmetric cryptosystems is referred to as **symmetric cryptography**. Symmetric cryptosystems are also sometimes referred to as **secret key cryptosystems**.

A few well-known examples of symmetric key encryption methods are − Digital Encryption Standard *DES*, Triple-DES *3DES*, IDEA, and BLOWFISH.



The salient features of cryptosystem based on symmetric key encryption are −

- Persons using symmetric key encryption must share a common key prior to exchange of information.
- Keys are recommended to be changed regularly to prevent any attack on the system.
- A robust mechanism needs to exist to exchange the key between the communicating parties. As keys are required to be changed regularly, this mechanism becomes expensive and cumbersome.
- In a group of **n** people, to enable two-party communication between any two persons, the number of keys required for group is **n × n - 1/2**.
- Length of Key number of bits in this encryption is smaller and hence, process of encryption-decryption is faster than asymmetric key encryption.
- Processing power of computer system required to run symmetric algorithm is less.

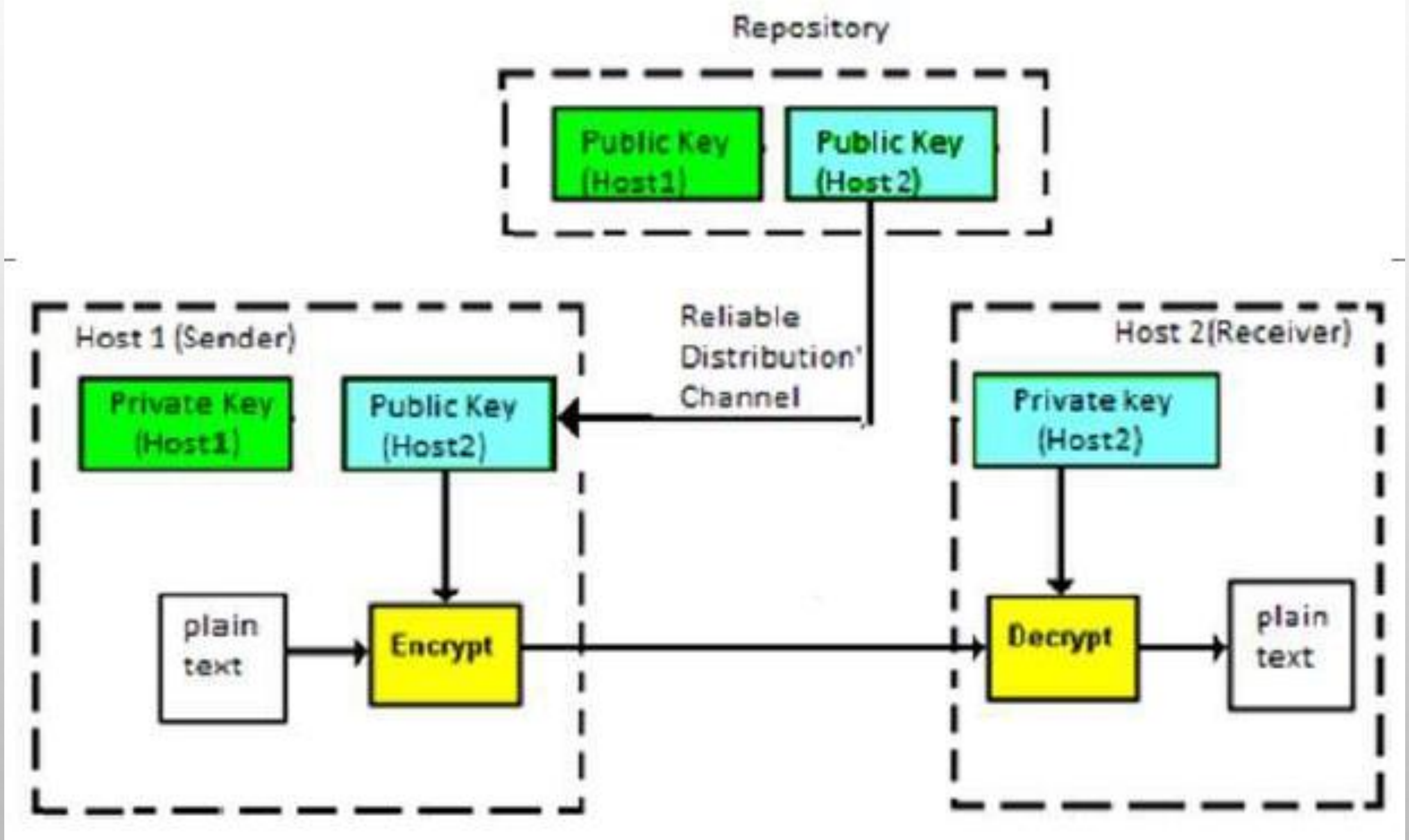
Challenge of Symmetric Key Cryptosystem

There are two restrictive challenges of employing symmetric key cryptography.

- **Key establishment** − Before any communication, both the sender and the receiver need to agree on a secret symmetric key. It requires a secure key establishment mechanism in place.
- **Trust Issue** − Since the sender and the receiver use the same symmetric key, there is an implicit requirement that the sender and the receiver 'trust' each other. For example, it may happen that the receiver has lost the key to an attacker and the sender is not informed.

Asymmetric Key Encryption

- The encryption process where **different keys are used for encrypting and decrypting the information** is known as Asymmetric Key Encryption. Though the keys are different, they are mathematically related and hence, retrieving the plaintext by decrypting ciphertext is feasible. The process is depicted in the following illustration −



Asymmetric Key Encryption was invented in the 20th century to come over the necessity of pre-shared secret key between communicating persons. The salient features of this encryption scheme are as follows −

- Every user in this system needs to have a pair of dissimilar keys, **private key** and **public key**. These keys are mathematically related − when one key is used for encryption, the other can decrypt the ciphertext back to the original plaintext.
- It requires to put the public key in public repository and the private key as a well-guarded secret. Hence, this scheme of encryption is also called **Public Key Encryption**.
- Though public and private keys of the user are related, it is computationally not feasible to find one from another. This is a strength of this scheme.
- When *Host1* needs to send data to *Host2,* he obtains the public key of *Host2* from repository, encrypts the data, and transmits.
- *Host2* uses his private key to extract the plaintext.
- Length of Keys number of bits in this encryption is large and hence, the process of encryption-decryption is slower than symmetric key encryption.
- Processing power of computer system required to run asymmetric algorithm is higher.

Relation between Encryption Schemes

A summary of basic key properties of two types of cryptosystems is given below –

	Symmetric Cryptosystems	Public Key Cryptosystems
Relation between Keys	Same	Different, but mathematically related
Encryption Key	Symmetric	Public
Decryption Key	Symmetric	Private

ATTACKS ON CRYPTOSYSTEMS

Attacks are typically categorized based on the action performed by the attacker.

Passive Attacks

These actions are passive in nature, as they neither affect information nor disrupt the communication channel.

A passive attack is often seen as *stealing* information.

Active Attacks

An active attack involves changing the information in some way by conducting some process on the information. For example,

- Modifying the information in an unauthorized manner.
- Initiating unintended or unauthorized transmission of information.
- Alteration of authentication data such as originator name or timestamp associated with information
- Unauthorized deletion of data.
- Denial of access to information for legitimate users denial of service.

TRADITIONAL CIPHERS

Earlier Cryptographic Systems

some facts about historical cryptosystems −

- All of these systems are **based on symmetric key encryption** scheme.
- The only security service these systems provide is confidentiality of information.
- Unlike modern systems which are digital and treat data as binary numbers, the earlier systems worked on alphabets as basic element.

Caesar Cipher

It is a mono-alphabetic cipher wherein each letter of the plaintext is substituted by another letter to form the ciphertext. It is a simplest form of substitution cipher scheme.

This cryptosystem is generally referred to as the **Shift Cipher**. The concept is to replace each alphabet by another alphabet which is 'shifted' by some fixed number between 0 and 25.

For this type of scheme, both sender and receiver agree on a 'secret shift number' for shifting the alphabet. This number which is between 0 and 25 becomes the key of encryption.

The name 'Caesar Cipher' is occasionally used to describe the Shift Cipher when the 'shift of three' is used.

Process of Shift Cipher

- In order to encrypt a plaintext letter, the sender positions the sliding ruler underneath the first set of plaintext letters and slides it to LEFT by the number of positions of the secret shift.
- The plaintext letter is then encrypted to the ciphertext letter on the sliding ruler underneath. The result of this process is depicted in the following illustration for an agreed shift of three positions. In this case, the plaintext 'tutorial' is encrypted to the ciphertext 'WXWRULDO'. Here is the ciphertext alphabet for a Shift of 3 −

Plaintext Alphabet	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
Ciphertext Alphabet	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

- On receiving the ciphertext, the receiver who also knows the secret shift, positions his sliding ruler underneath the ciphertext alphabet and slides it to RIGHT by the agreed shift number, 3 in this case.
- He then replaces the ciphertext letter by the plaintext letter on the sliding ruler underneath. Hence the ciphertext 'WXWRULDO' is decrypted to 'tutorial'. To decrypt a message encoded with a Shift of 3, generate the plaintext alphabet using a shift of '-3' as shown below −

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

Transposition Cipher

It is another type of cipher where the order of the alphabets in the plaintext is rearranged to create the ciphertext. The actual plaintext alphabets are not replaced.

For example, the plaintext is “golden statue is in eleventh cave” and the secret random key chosen is “five”. We arrange this text horizontally in table with number of column equal to key value. The resulting text is shown below.

g	o	l	d	e
n	s	t	a	t
u	e	i	s	i
n	e	l	e	v
e	n	t	h	c
a	v	e		

MODERN SYMMETRIC KEY ENCRYPTION

Digital data is represented in strings of binary digits bits unlike alphabets.

Modern cryptosystems need to process this binary strings to convert in to another binary string.

Based on how these binary strings are processed,

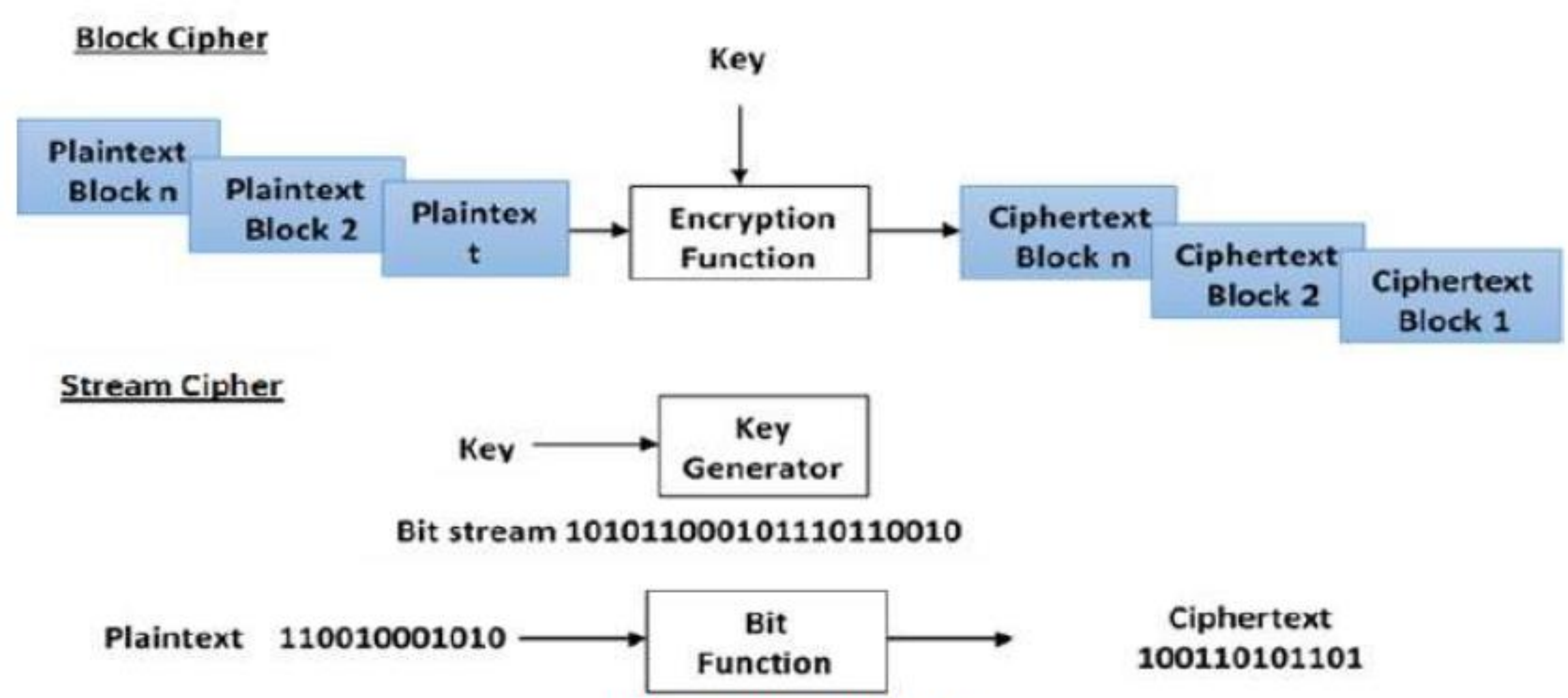
a symmetric encryption schemes can be classified in to −

Block Ciphers

In this scheme, the plain binary text is processed in blocks groups of bits at a time; i.e. a block of plaintext bits is selected, a series of operations is performed on this block to generate a block of ciphertext bits. The number of bits in a block is fixed. For example, the schemes DES and AES have block sizes of 64 and 128, respectively.

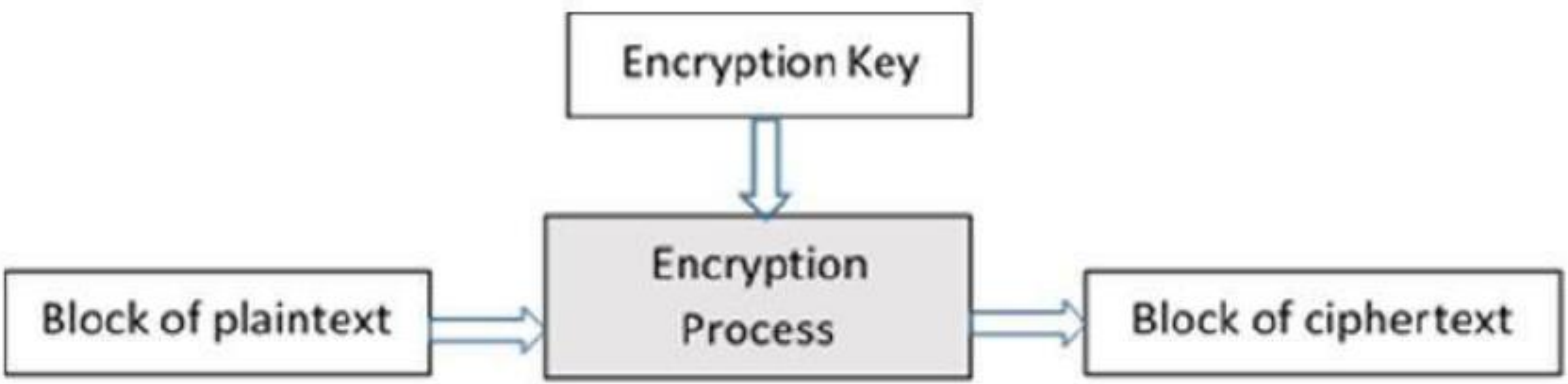
Stream Ciphers

In this scheme, the plaintext is processed one bit at a time i.e. one bit of plaintext is taken, and a series of operations is performed on it to generate one bit of ciphertext. Technically, stream ciphers are block ciphers with a block size of one bit.



BLOCK CIPHER

The basic scheme of a block cipher is depicted as follows –



Block Size

Though any size of block is acceptable, following aspects are borne in mind while selecting a size of a block.

- **Avoid very small block size** − Say a block size is m bits. Then the possible plaintext bits combinations are then 2^m. If the attacker discovers the plain text blocks corresponding to some previously sent ciphertext blocks, then the attacker can launch a type of 'dictionary attack' by building up a dictionary of plaintext/ciphertext pairs sent using that encryption key. A larger block size makes attack harder as the dictionary needs to be larger.

- **Do not have very large block size** − With very large block size, the cipher becomes inefficient to operate. Such plaintexts will need to be padded before being encrypted.

- **Multiples of 8 bit** − A preferred block size is a multiple of 8 as it is easy for implementation as most computer processor handle data in multiple of 8 bits.

Padding in Block Cipher

Block ciphers process blocks of fixed sizes say 64 bits. The length of plaintexts is mostly not a multiple of the block size. For example, a 150-bit plaintext provides two blocks of 64 bits each with third block of balance 22 bits. The last block of bits needs to be padded up with redundant information so that the length of the final block equal to block size of the scheme. In our example, the remaining 22 bits need to have additional 42 redundant bits added to provide a complete block. The process of adding bits to the last block is referred to as **padding**.

Block Cipher Schemes

There is a vast number of block ciphers schemes that are in use. Many of them are publically known. Most popular and prominent block ciphers are listed below.

- **Digital Encryption Standard** DES – The popular block cipher of the 1990s. It is now considered as a 'broken' block cipher, due primarily to its small key size.
- **Triple DES** – It is a variant scheme based on repeated DES applications. It is still a respected block ciphers but inefficient compared to the new faster block ciphers available.
- **Advanced Encryption Standard** AES – It is a relatively new block cipher based on the encryption algorithm **Rijndael** that won the AES design competition.
- **IDEA** – It is a sufficiently strong block cipher with a block size of 64 and a key size of 128 bits. A number of applications use IDEA encryption, including early versions of Pretty Good Privacy PGP protocol. The use of IDEA scheme has a restricted adoption due to patent issues.
- **Twofish** – This scheme of block cipher uses block size of 128 bits and a key of variable length. It was one of the AES finalists. It is based on the earlier block cipher Blowfish with a block size of 64 bits.
- **Serpent** – A block cipher with a block size of 128 bits and key lengths of 128, 192, or 256 bits, which was also an AES competition finalist. It is a slower but has more secure design than other block cipher.

BLOCK CIPHER MODES OF OPERATION

A block cipher processes the data blocks of fixed size. Usually, the size of a message is larger than the block size. Hence, the long message is divided into a series of sequential message blocks, and the cipher operates on these blocks one at a time.

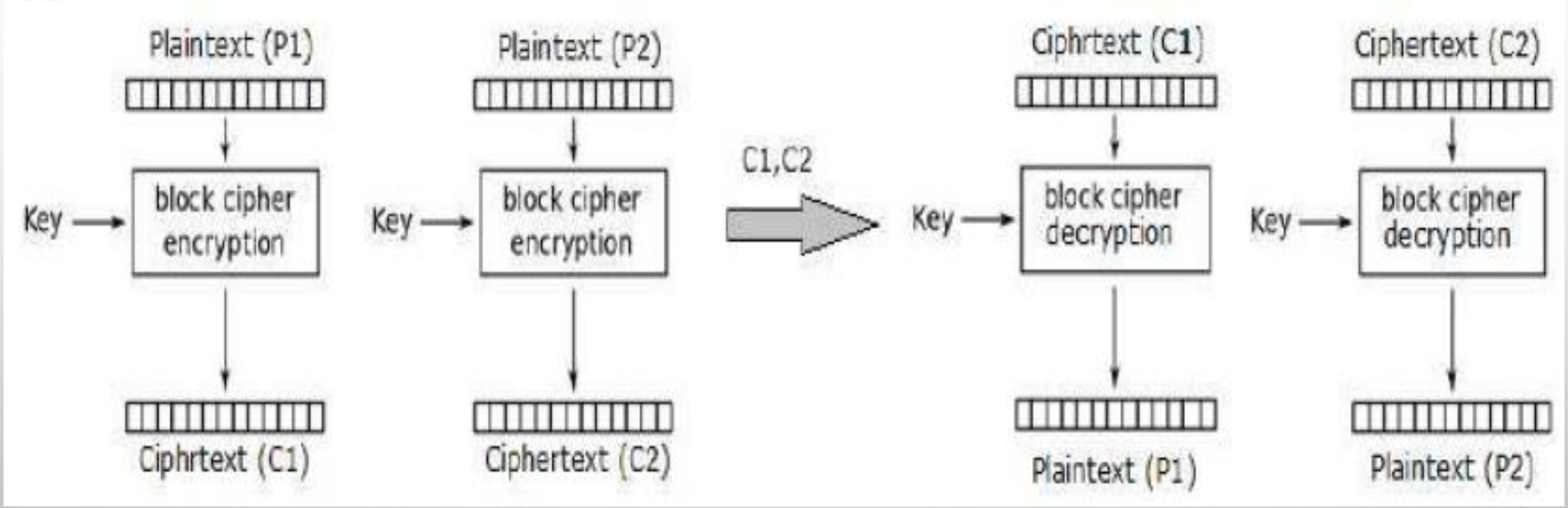
Electronic Code Book ECB Mode

This mode is a most straightforward way of processing a series of sequentially listed message blocks.

Operation

- The user takes the first block of plaintext and encrypts it with the key to produce the first block of ciphertext.
- He then takes the second block of plaintext and follows the same process with same key and so on so forth.

The ECB mode is **deterministic**, that is, if plaintext block P1, P2,..., Pm are encrypted twice under the same key, the output ciphertext blocks will be the same.



Plaintext (P1)
Key
block cipher encryption
Ciphrtext (C1)
Plaintext (P2)
Key
block cipher encryption
Ciphertext (C2)
C1,C2
Ciphrtext (C1)
Key
block cipher decryption
Plaintext (P1)
Ciphertext (C2)
Key
block cipher decryption
Plaintext (P2)

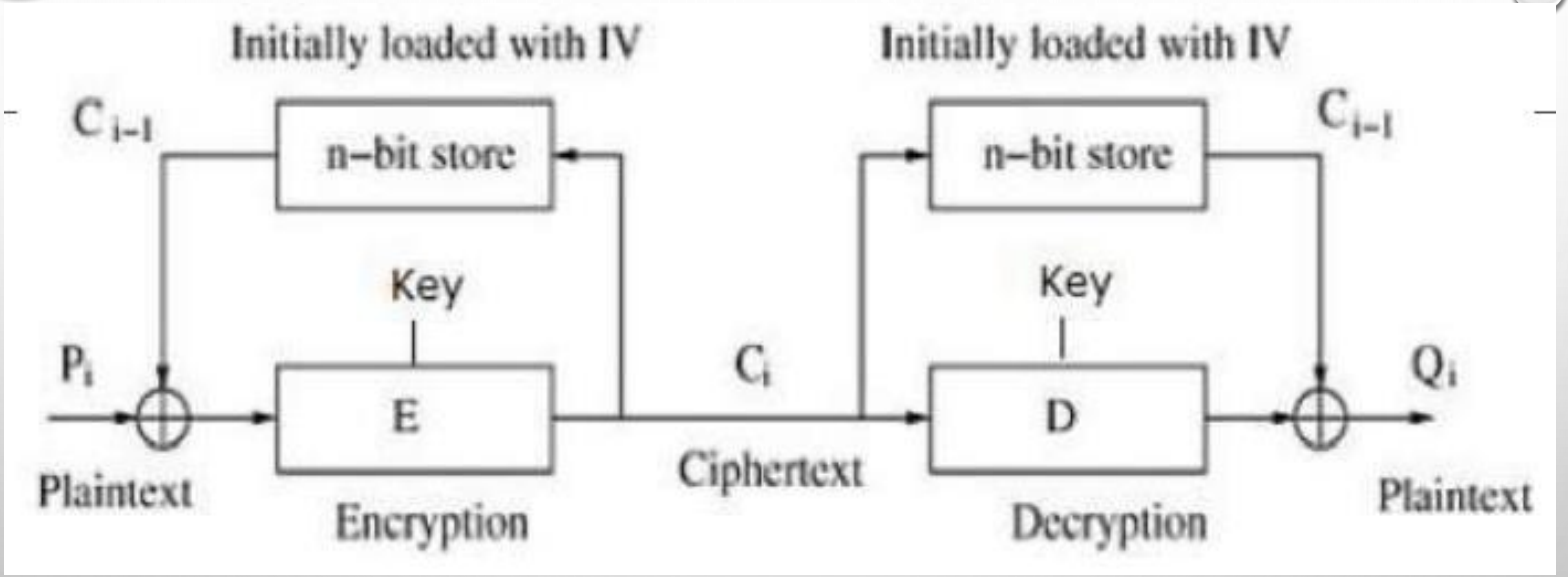
Cipher Block Chaining CBC Mode

CBC mode of operation provides message dependence for generating ciphertext and makes the system non-deterministic.

Operation

The operation of CBC mode is depicted in the following illustration. The steps are as follows −

- Load the n-bit Initialization Vector IV in the top register.
- XOR the n-bit plaintext block with data value in top register.
- Encrypt the result of XOR operation with underlying block cipher with key K.
- Feed ciphertext block into top register and continue the operation till all plaintext blocks are processed.
- For decryption, IV data is XORed with first ciphertext block decrypted. The first ciphertext block is also fed into to register replacing IV for decrypting next ciphertext block.


Initially loaded with IV
Initially loaded with IV
C i-1
n–bit store
n–bit store
C i-1
Key
Key
P i
E
C i
D
Q i
Plaintext
Encryption
Ciphertext
Decryption
Plaintext

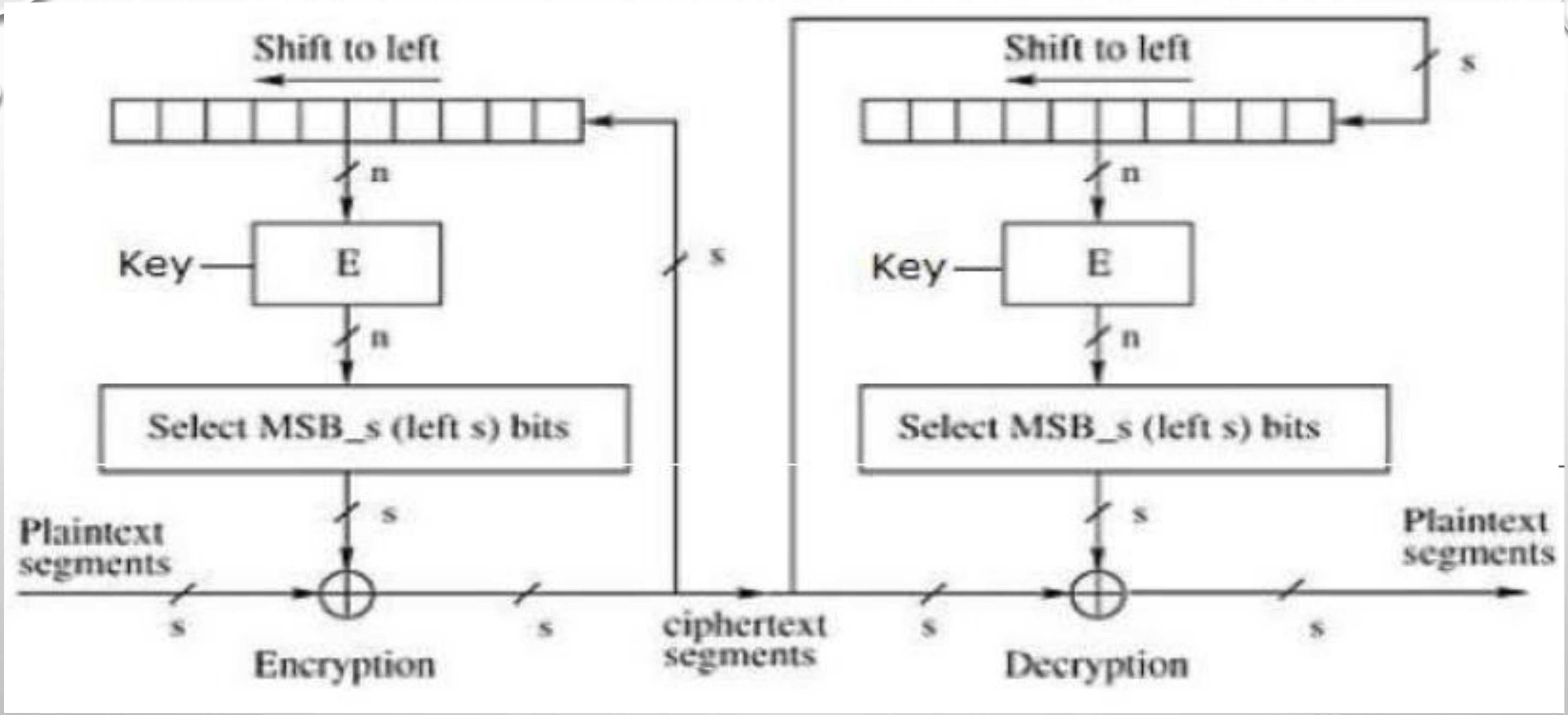
Cipher Feedback CFB Mode

In this mode, each ciphertext block gets 'fed back' into the encryption process in order to encrypt the next plaintext block.

Operation

The operation of CFB mode is depicted in the following illustration. For example, in the present system, a message block has a size 's' bits where 1 < s < n. The CFB mode requires an initialization vector IV as the initial random n-bit input block. The IV need not be secret. Steps of operation are −

- Load the IV in the top register.
- Encrypt the data value in top register with underlying block cipher with key K.
- Take only 's' number of most significant bits left bits of output of encryption process and XOR them with 's' bit plaintext message block to generate ciphertext block.
- Feed ciphertext block into top register by shifting already present data to the left and continue the operation till all plaintext blocks are processed.
- Essentially, the previous ciphertext block is encrypted with the key, and then the result is XORed to the current plaintext block.
- Similar steps are followed for decryption. Pre-decided IV is initially loaded at the start of decryption.


Shift to left
n
Key
E
n
Select MSB_s (left s) bits
s
Plaintext segments
s
s
s
Encryption
ciphertext segments
s
Shift to left
n
Key
E
n
Select MSB_s (left s) bits
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Plaintext segments
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s
Decryption