CRYPTOGRAPHY

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'We can only see a short distance ahead, but we can see plenty there that needs to be done'

Alan Turing

Abstract

Cryptography — the science of secret writing — is an ancient art; the first documented use of cryptography in writing dates back to circa 1900 B.C. when an Egyptian scribe used non-standard hieroglyphs in an inscription. Some experts argue that cryptography appeared spontaneously sometime after writing was invented, with applications ranging from diplomatic missives to war-time battle plans. It is no surprise, then, that new forms of cryptography came soon after the widespread development of computer communications. In data and telecommunications, cryptography is necessary when communicating over any untrusted medium, which includes just about any network, particularly the Internet.

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1 Glossary

1.1 Cryptography

The transformed message cipher an algorithm for transforming an intelligible message into one that is unintelligible by transposition and/or substitution methods the art or science encompassing the principles and methods of transforming an intelligible message into one that is unintelligible, and then re-transforming that message back to its original form.

1.2 Cryptanalysis

The study of principles and methods of transforming an unintelligible message back into an intelligible message without knowledge of the key. Also called codebreaking.

1.3 Cryptology

The sum of both cryptography and cryptanalysis.

1.4 Cryptosystem

A system which converts plain text to cipher text or cipher text to plain text by the application of encryption or decryption algorithm. The key generation for encryption and decryption algorithms is also a part of the cryptosystem.

1.5 Key

Some critical information used by the cipher, known only to the sender and receiver.

1.6 Code

An algorithm for transforming an intelligible message into an unintelligible one using a code-book.

1.7 Decipher (Decode)

The process of converting ciphertext back into plaintext using a cipher and a key.

1.8 Encipher (Encode)

The process of converting plaintext to ciphertext using a cipher and a key.

1.9 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.

1.10 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.

1.11 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.

1.12 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.

1.13 Interceptor

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.

1.14 Plaintext

The original intelligible message. It is the data to be protected during transmission.

1.15 Ciphertext

The transformed message cipher an algorithm for transforming an intelligible message into one that is unintelligible by transposition and/or substitution methods. 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.

1.16 Notation

P	plaintext
C	ciphertext
E	the encryption method
D	the decryption method
k	the key

2 Introduction To Cryptography and Related Topics

2.1 Cryptography

Cryptography, or cryptology, is the practice and study of techniques for secure communication in the presence of third parties called adversaries. More generally, cryptography is about constructing and analysing protocols that prevent third parties or the public from reading private messages; various aspects in information security such as data confidentiality, data integrity, authentication, and non-repudiation are central to modern cryptography. Modern cryptography exists at the intersection of the disciplines of mathematics, computer science, electrical engineering, communication science, and physics. Applications of cryptography include electronic commerce, chip-based payment cards, digital currencies, computer passwords, and military communications. There are five primary functions of cryptography:

Privacy/Confidentiality	Ensuring that no one can read the message except the intended receiver.
Authentication	The process of proving one's identity.
Integrity	Assuring the receiver that the received message has not been altered in any way.
Non-repudiation	A mechanism to prove that the sender really.
Key exchange	The method by which crypto keys are shared between sender and receiver.

2.1.1 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.

1. **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.

2. **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 accidentally. 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.

3. **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. Apart from the originator, authentication may also provide assurance about other parameters related to data such as the date and time of creation/transmission. Authentication service has two variants –

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

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

4. **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.

In cryptography, we start with the unencrypted data, referred to as plaintext. Plaintext is encrypted into ciphertext, which will in turn (usually) be decrypted back into usable plaintext. The encryption and decryption is based upon the type of cryptography scheme being employed and some form of key. For those who like formulas, this process is sometimes written as:

$$C = E_k(P)$$

$$P = D_k(C)$$

where,

P = plaintext,

C = ciphertext,

E = the encryption method,

D = the decryption method,

k = the key.

Given this, there are other functions that might be supported by crypto and other terms that one might hear:

- ⋆ **Forward Secrecy (aka Perfect Forward Secrecy):** This feature protects past encrypted sessions from compromise even if the server holding the messages is compromised. This is accomplished by creating a different key for every session so that compromise of a single key does not threaten the entirely of the communications.
- ⋆ **Perfect Security:** A system that is unbreakable and where the ciphertext conveys no information about the plaintext or the key. To achieve perfect security, the key has to be at least as long as the plaintext, making analysis and even brute-force attacks impossible. One-time pads are an example of such a system.
- ⋆ **Deniable Authentication (aka Message Repudiation):** A method whereby participants in an exchange of messages can be assured in the authenticity of the messages but in such a way that senders can later plausibly deny their participation to a third-party.

In many of the descriptions below, two communicating parties will be referred to as Alice and Bob; this is the common nomenclature in the crypto field and literature to make it easier to identify the communicating parties. If there is a third and fourth party to the communication, they will be referred to as Carol and Dave, respectively. A malicious party is referred to as Mallory, an eavesdropper as Eve, and a trusted third party as Trent.

Finally, cryptography is most closely associated with the development and creation of the mathematical algorithms used to encrypt and decrypt messages, whereas cryptanalysis is the science of analysing and breaking encryption schemes. Cryptology is the umbrella term referring to the broad study of secret writing, and encompasses both cryptography and cryptanalysis.

2.1.2 Ancient 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 fuelled 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.

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 (three was a common choice), the recipient of this message would then shift the letters back by the same number and obtain the original message.

2.1.3 Evolution of Cryptography

It is during and after the European Renaissance, various Italian and Papal states led the rapid proliferation of cryptographic techniques. Various analysis and attack techniques were researched in this era to break the secret codes.

⋆ 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.

With the advances taking place in this field, government organizations, military units, and some corporate houses started adopting the applications of cryptography. They used cryptography to guard their secrets from others. Now, the arrival of computers and the Internet has brought effective cryptography within the reach of common people.

2.1.4 Modern Cryptography

Modern cryptography is the cornerstone of computer and communications security. Its foundation is based on various concepts of mathematics such as number theory, computational-complexity theory, and probability theory.

2.1.5 Characteristics of Modern and Ancient Cryptography

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.

2.1.6 Cryptography Primitives

Cryptography primitives[1] 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 functions	Message Authentication codes (MAC)	Digital Signatures
Confidentiality	Yes	No	No	No
Integrity	No	Sometimes	Yes	Yes
Authentication	No	No	Yes	Yes
Non Reputation	No	No	Sometimes	Yes

2.2 Cryptanalysis

Cryptanalysis is the study of analysing information systems in order to study the hidden aspects of the systems. Cryptanalysis is used to breach cryptographic security systems and gain access to the contents of encrypted messages, even if the cryptographic key is unknown. In addition to mathematical analysis of cryptographic algorithms, cryptanalysis includes the study of side-channel attacks that do not target weaknesses in the cryptographic algorithms themselves, but instead exploit weaknesses in their implementation.

[1]Cryptographic Primitives are intricately related and they are often combined to achieve a set of desired security services from a cryptosystem.

2.3 Cryptosystem

A cryptosystem[2] 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.

2.4 Steganography

Steganography is the practice of concealing a message within another message or a physical object. In computing/electronic contexts, a computer file, message, image, or video is concealed within another file, message, image, or video.

Generally, the hidden messages appear to be (or to be part of) something else: images, articles, shopping lists, or some other cover text. For example, the hidden message may be in invisible ink between the visible lines of a private letter. Some implementations of steganography that lack a shared secret are forms of security through obscurity, and key-dependent steganographic schemes adhere to Kerckhoffs's principle. The advantage of steganography over cryptography alone is that the intended secret message does not attract attention to itself as an object of scrutiny. Plainly visible encrypted messages, no matter how unbreakable they are, arouse interest and may in themselves be incriminating in countries in which encryption is illegal. Whereas cryptography is the practice of protecting the contents of a message alone, steganography is concerned with concealing the fact that a secret message is being sent and its contents.

Steganography includes the concealment of information within computer files. In digital steganography, electronic communications may include steganographic coding inside of a transport layer, such as a document file, image file, program, or protocol. Media files are ideal for steganographic transmission because of their large size. For example, a sender might start with an innocuous image file and adjust the colour of every hundredth pixel to correspond to a letter in the alphabet. The change is so subtle that someone who is not specifically looking for it is unlikely to notice the change.

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

3 Types of Cryptography

3.1 Private-Key Cryptography

Symmetric-key algorithms are algorithms for cryptography that use the same cryptographic keys for both the encryption of plaintext and the decryption of ciphertext. The keys may be identical, or there may be a simple transformation to go between the two keys. The keys, in practice, represent a shared secret between two or more parties that can be used to maintain a private information link. The requirement that both parties have access to the secret key is one of the main drawbacks of symmetric-key encryption, in comparison to public-key encryption (also known as asymmetric-key encryption).

$$P \xrightarrow{\textbf{private key}} C \xrightarrow{\textbf{private key}} P$$

3.1.1 Challenge of Private-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.

These two challenges are highly restraining for modern day communication. Today, people need to exchange information with non-familiar and non-trusted parties. For example, a communication between online seller and customer. These limitations of symmetric key encryption gave rise to asymmetric key encryption schemes.

3.2 Public-Key Cryptography

Public-key cryptography, or asymmetric cryptography, is a cryptographic system that uses pairs of keys: public keys (which may be known to others), and private keys (which may never be known by any except the owner). The generation of such key pairs depends on cryptographic algorithms which are based on mathematical problems termed one-way functions. Effective security requires keeping the private key private; the public key can be openly distributed without compromising security.

In such a system, any person can encrypt a message using the intended receiver's public key, but that encrypted message can only be decrypted with the receiver's private key. This allows, for instance, a server program to generate a cryptographic key intended for a suitable symmetric-key cryptography, then to use a client's openly-shared public key to encrypt that newly generated symmetric key. The server can then send this encrypted symmetric key over an insecure channel to the client; only the client can decrypt it using the client's private key (which pairs with the public key used by the server to encrypt the message). With the client and server both having the same symmetric key, they can safely use symmetric key encryption (likely much faster) to communicate over otherwise-insecure channels. This scheme has the advantage of not having to manually pre-share symmetric keys (a fundamentally difficult problem) while gaining the higher data throughput advantage of symmetric-key cryptography.

With public-key cryptography, robust authentication is also possible. A sender can combine a message with a private key to create a short digital signature on the message. Anyone with the sender's corresponding public key can combine that message with a claimed digital signature; if the signature matches the message, the origin of the message is verified (i.e., it must have been made by the owner of the corresponding private key).

Public key algorithms are fundamental security primitives in modern cryptosystems, including applications and protocols which offer assurance of the confidentiality, authenticity and non-availability of electronic communications and data storage. They underpin numerous Internet standards, such as Transport Layer Security (TLS), S/MIME, PGP, and GPG. Some public key algorithms provide key distribution and secrecy (e.g., Diffie–Hellman key exchange), some provide digital signatures (e.g., Digital Signature Algorithm), and some provide both (e.g., RSA). Compared to symmetric encryption, asymmetric encryption is rather slower than good symmetric encryption, too slow for many purposes. Today's cryptosystems (such as TLS, Secure Shell) use both symmetric encryption and asymmetric encryption.

$$P \xrightarrow{\textbf{public key}} C \xrightarrow{\textbf{private key}} P$$

3.2.1 Challenge of Public-Key Cryptosystem

Public-key cryptosystems have one significant challenge − the user needs to trust that the public key that he is using in communications with a person really is the public key of that person and has not been spoofed by a malicious third party.

This is usually accomplished through a Public Key Infrastructure (PKI) consisting a trusted third party. The third party securely manages and attests to the authenticity of public keys. When the third party is requested to provide the public key for any communicating person $\mathbb{X}$, they are trusted to provide the correct public key.

The third party satisfies itself about user identity by the process of attestation, notarization, or some other process − that $\mathbb{X}$ is the one and only, or globally unique, $\mathbb{X}$. The most common method of making the verified public keys available is to embed them in a certificate which is digitally signed by the trusted third party.

3.2.2 Kerckhoff's Principle

Kerckhoff's Principle for Cryptosystem In the 19$^{\text{th}}$ century, a Dutch cryptographer Auguste Kerckhoff furnished the requirements of a good cryptosystem. Kerckhoff stated that a cryptographic system should be secure even if everything about the system, except the key, is public knowledge.

The six design principles defined by Kerckhoff for cryptosystem are −

- ⋆ The cryptosystem should be unbreakable practically, if not mathematically.
- ⋆ Falling of the cryptosystem in the hands of an intruder should not lead to any compromise of the system, preventing any inconvenience to the user.
- ⋆ The key should be easily communicable, memorable, and changeable.
- ⋆ The ciphertext should be transmissible by telegraph, an unsecure channel.
- ⋆ The encryption apparatus and documents should be portable and operable by a single person.
- ⋆ Finally, it is necessary that the system be easy to use, requiring neither mental strain nor the knowledge of a long series of rules to observe.

The second rule is currently known as Kerckhoff principle. It is applied in virtually all the contemporary encryption algorithms such as DES, AES, etc. These public algorithms are considered to be thoroughly secure. The security of the encrypted message depends solely on the security of the secret encryption key. Keeping the algorithms secret may act as a significant barrier to cryptanalysis. However, keeping the algorithms secret is possible only when they are used in a strictly limited circle. In modern era, cryptography needs to cater to users who are connected to the Internet. In such cases, using a secret algorithm is not feasible, hence Kerckhoff principles became essential guidelines for designing algorithms in modern cryptography.

3.3 Hash Function

A hash function is any function that can be used to map data of arbitrary size to fixed-size values. The values returned by a hash function are called hash values, hash codes, digests, or simply hashes. The values are usually used to index a fixed-size table called a hash table. Use of a hash function to index a hash table is called hashing or scatter storage addressing.

Hash functions and their associated hash tables are used in data storage and retrieval applications to access data in a small and nearly constant time per retrieval, and require an amount of storage space only fractionally greater than the total space required for the data or records themselves. Hashing is a computationally and storage space efficient form of data access which avoids the non-linear access time of ordered and unordered lists and structured trees, and the often exponential storage requirements of direct access of state spaces of large or variable-length keys.

Use of hash functions relies on statistical properties of key and function interaction: worst case behaviour is intolerably bad with a vanishingly small probability, and average case behaviour can be nearly optimal (minimal collision).

Hash functions are related to (and often confused with) checksums, check digits, fingerprints, lossy compression, randomization functions, error-correcting codes, and ciphers. Although the concepts overlap to some extent, each one has its own uses and requirements and is designed and optimized differently. The hash functions differ from the concepts numbered mainly in terms of data integrity.

$$P \xrightarrow{\textbf{hash function}} C$$

3.4 Relation between Encryption Schemes

	Private-Key Cryptosystems	**Public-Key Cryptosystems**
Relation between Keys	Equal	Not Equal, but mathematically related
Encryption Key	Private/Symmetric	Public/Asymmetric
Decryption Key	Private/Symmetric	Private/Asymmetric

3.5 Attacks on Cryptosystems

Attacks are typically categorized based on the action performed by the attacker. An attack, thus, can be passive or active.

3.5.1 Passive Attacks

The main goal of a passive attack is to obtain unauthorized access to the information. For example, actions such as intercepting and eavesdropping on the communication channel can be regarded as passive attack. 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. The only difference in stealing physical goods and stealing information is that theft of data still leaves the owner in possession of that data. Passive information attack is thus more dangerous than stealing of goods, as information theft may go unnoticed by the owner.

3.5.2 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).

3.6 Assumptions of Attacker

Let us see the prevailing environment around cryptosystems followed by the types of attacks employed to break these systems :

3.6.1 Environment around Cryptosystem

While considering possible attacks on the cryptosystem, it is necessary to know the cryptosystems environment. The attacker's assumptions and knowledge about the environment decides his capabilities.

In cryptography, the following three assumptions are made about the security environment and attacker's capabilities.

1. **Details of the Encryption Scheme**

   The design of a cryptosystem is based on the following two cryptography algorithms –

   (a) **Public Algorithms –** With this option, all the details of the algorithm are in the public domain, known to everyone.

   (b) **Proprietary Algorithms –** The details of the algorithm are only known by the system designers and users.

In case of proprietary algorithms, security is ensured through obscurity. Private algorithms may not be the strongest algorithms as they are developed in-house and may not be extensively investigated for weakness.

Secondly, they allow communication among closed group only. Hence they are not suitable for modern communication where people communicate with large number of known or unknown entities. Also, according to Kerckhoff's principle, the algorithm is preferred to be public with strength of encryption lying in the key. Thus, the first assumption about security environment is that the encryption algorithm is known to the attacker.

2. **Availability of Ciphertext**

   We know that once the plaintext is encrypted into ciphertext, it is put on unsecure public channel for transmission. Thus, the attacker can obviously assume that it has access to the ciphertext generated by the cryptosystem.

3. **Availability of Plaintext and Ciphertext**

   This assumption is not as obvious as other. However, there may be situations where an attacker can have access to plaintext and corresponding ciphertext. Some such possible circumstances are —

   (a) The attacker influences the sender to convert plaintext of his choice and obtains the ciphertext.

   (b) The receiver may divulge the plaintext to the attacker inadvertently. The attacker has access to corresponding ciphertext gathered from open channel.

   (c) In a public-key cryptosystem, the encryption key is in open domain and is known to any potential attacker. Using this key, he can generate pairs of corresponding plaintexts and ciphertexts.

3.7 Cryptographic Attacks

The basic intention of an attacker is to break a cryptosystem and to find the plaintext from the ciphertext. To obtain the plaintext, the attacker only needs to find out the secret decryption key, as the algorithm is already in public domain. Hence, he applies maximum effort towards finding out the secret key used in the cryptosystem. Once the attacker is able to determine the key, the attacked system is considered as broken or compromised.

Based on the methodology used, attacks on cryptosystems are categorized as follows –

3.7.1 Ciphertext Only Attacks (COA)

In this method, the attacker has access to a set of ciphertext(s). He does not have access to corresponding plaintext. COA is said to be successful when the corresponding plaintext can be determined from a given set of ciphertext. Occasionally, the encryption key can be determined from this attack. Modern cryptosystems are guarded against ciphertext-only attacks.

3.7.2 Known Plaintext Attack (KPA)

In this method, the attacker knows the plaintext for some parts of the ciphertext. The task is to decrypt the rest of the ciphertext using this information. This may be done by determining the key or via some other method. The best example of this attack is linear cryptanalysis against block ciphers.

3.7.3 Chosen Plaintext Attack (CPA)

In this method, the attacker has the text of his choice encrypted. So he has the ciphertext-plaintext pair of his choice. This simplifies his task of determining the encryption key. An example of this attack is differential cryptanalysis applied against block ciphers as well as hash functions. A popular public key cryptosystem, RSA is also vulnerable to chosen-plaintext attacks.

3.7.4 Dictionary Attack

This attack has many variants, all of which involve compiling a 'dictionary'. In simplest method of this attack, attacker builds a dictionary of ciphertexts and corresponding plaintexts that he has learnt over a period of time. In future, when an attacker gets the ciphertext, he refers the dictionary to find the corresponding plaintext.

3.7.5 Brute Force Attack (BFA)

In this method, the attacker tries to determine the key by attempting all possible keys. If the key is 8 bits long, then the number of possible keys is $2^8 = 256$. The attacker knows the ciphertext and the algorithm, now he attempts all the 256 keys one by one for decryption. The time to complete the attack would be very high if the key is long.

3.7.6 Birthday Attack

This attack is a variant of brute-force technique. It is used against the cryptographic hash function. When students in a class are asked about their birthdays, the answer is one of the possible 365 dates. Let us assume the first student's birthdate is 3$^{\text{rd}}$ August. Then to find the next student whose birthdate is 3$^{\text{rd}}$ August, we need to enquire $1.25 \times \sqrt{365} \approx 25$ students. Similarly, if the hash function produces 64 bit hash values, the possible hash values are 1.8×1019. By repeatedly evaluating the function for different inputs, the same output is expected to be obtained after about 5.1×109 random inputs. If the attacker is able to find two different inputs that give the same hash value, it is a collision and that hash function is said to be broken.

3.7.7 Man in Middle Attack (MIM)

The targets of this attack are mostly public key cryptosystems where key exchange is involved before communication takes place.

- ⋆ Host $\mathbb{A}$ wants to communicate to host $\mathbb{B}$, hence requests public key of $\mathbb{B}$.
- ⋆ An attacker intercepts this request and sends his public key instead.
- ⋆ Thus, whatever host $\mathbb{A}$ sends to host $\mathbb{B}$, the attacker is able to read.
- ⋆ In order to maintain communication, the attacker re-encrypts the data after reading with his public key and sends to $\mathbb{B}$.
- ⋆ The attacker sends his public key as $\mathbb{A}$'s public key so that $\mathbb{B}$ takes it as if it is taking it from $\mathbb{A}$.

3.7.8 Side Channel Attack (SCA)

This type of attack is not against any particular type of cryptosystem or algorithm. Instead, it is launched to exploit the weakness in physical implementation of the cryptosystem.

3.7.9 Timing Attacks

They exploit the fact that different computations take different times to compute on processor. By measuring such timings, it is be possible to know about a particular computation the processor is carrying out. For example, if the encryption takes a longer time, it indicates that the secret key is long.

3.7.10 Power Analysis Attacks

These attacks are similar to timing attacks except that the amount of power consumption is used to obtain information about the nature of the underlying computations.

3.7.11 Fault analysis Attacks

In these attacks, errors are induced in the cryptosystem and the attacker studies the resulting output for useful information.

3.8 Practicality of Attacks

The attacks on cryptosystems described here are highly academic, as majority of them come from the academic community. In fact, many academic attacks involve quite unrealistic assumptions about environment as well as the capabilities of the attacker. For example, in chosen-ciphertext attack, the attacker requires an impractical number of deliberately chosen plaintext-ciphertext pairs. It may not be practical altogether. Nonetheless, the fact that any attack exists should be a cause of concern, particularly if the attack technique has the potential for improvement.

4 Symmetric Cryptosystems

4.0.1 Ancient Cryptosystems

Before proceeding further, we shall discuss 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.
- ⋆ These earlier cryptographic systems are also referred to as Ciphers. In general, a cipher is simply just a set of steps (an algorithm) for performing both an encryption, and the corresponding decryption.

4.1 Shift Ciphers

4.1.1 Caesar/Roman Emperors 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.

4.1.1.1 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 **'EXAMPLE'** is encrypted to the ciphertext **'HADPSOH'**. Here is the ciphertext alphabet for a Shift of 3 :

P_t	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
C_t	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 **'HADPSOH'** is decrypted to **'EXAMPLE'**. To decrypt a message encoded with a Shift of 3, generate the plaintext alphabet using a shift of '-3' as shown below –

P_t	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
C_t	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

4.1.1.2 Algorithm

Encryption: $C \equiv E(k, P) \equiv (P + k) \bmod 26$

Decryption: $P \equiv D(k, C) \equiv (C - k) \bmod 26$

4.1.1.3 Security Value : Caesar Cipher is not a secure cryptosystem because there are only 26 possible keys to try out. An attacker can carry out an exhaustive key search with available limited computing resources.

4.1.2 ROT13

Rotation 13 (ROT13)[3] is a simple letter substitution cipher that replaces a letter with the 13^{th} letter after it in the alphabet. ROT13 is a special case of the Caesar cipher. Because there are 26 letters (2×13) in the basic Latin alphabet, ROT13 is its own inverse; that is, to undo ROT13, the same algorithm is applied, so the same action can be used for encoding and decoding.

4.1.2.1 Algorithm

Encryption: $C \equiv E(P, k = 13) \equiv (P + 13) \bmod 26$

Decryption: $P \equiv D(C, k = 13) \equiv (C - 13) \bmod 26$

4.1.2.2 Security Value : ROT13 cipher algorithm is considered as special case of Caesar Cipher. It is not a very secure algorithm and can be broken easily with frequency analysis or by just trying possible 25 keys whereas ROT13 can be broken by shifting 13 places. Therefore, it does not include any practical use. The algorithm provides virtually no cryptographic security, and is often cited as a canonical example of weak encryption.

4.1.3 ROT47

Rotation 47 (ROT47)[4] is a derivative of ROT13 which, in addition to scrambling the basic letters, treats numbers and common symbols. Instead of using the sequence A–Z as the alphabet, ROT47 uses a larger set of characters from the common character encoding known as ASCII. Specifically, the 7-bit printable characters, excluding space, from decimal 33 '!' through 126 '~', 94 in total, taken in the order of the numerical values of their ASCII codes, are rotated by 47 positions, without special consideration of case. For example, the character A is mapped to p, while a is mapped to 2. The use of a larger alphabet produces a more thorough obfuscation than that of ROT13. On the other hand, because ROT47 introduces numbers and symbols into the mix without discrimination, it is more immediately obvious that the text has been enciphered.

Security Value : Though far stronger than ROT13. It is still a type of shift cipher and hence can be deciphered using frequency analysis and exhaustive key search.

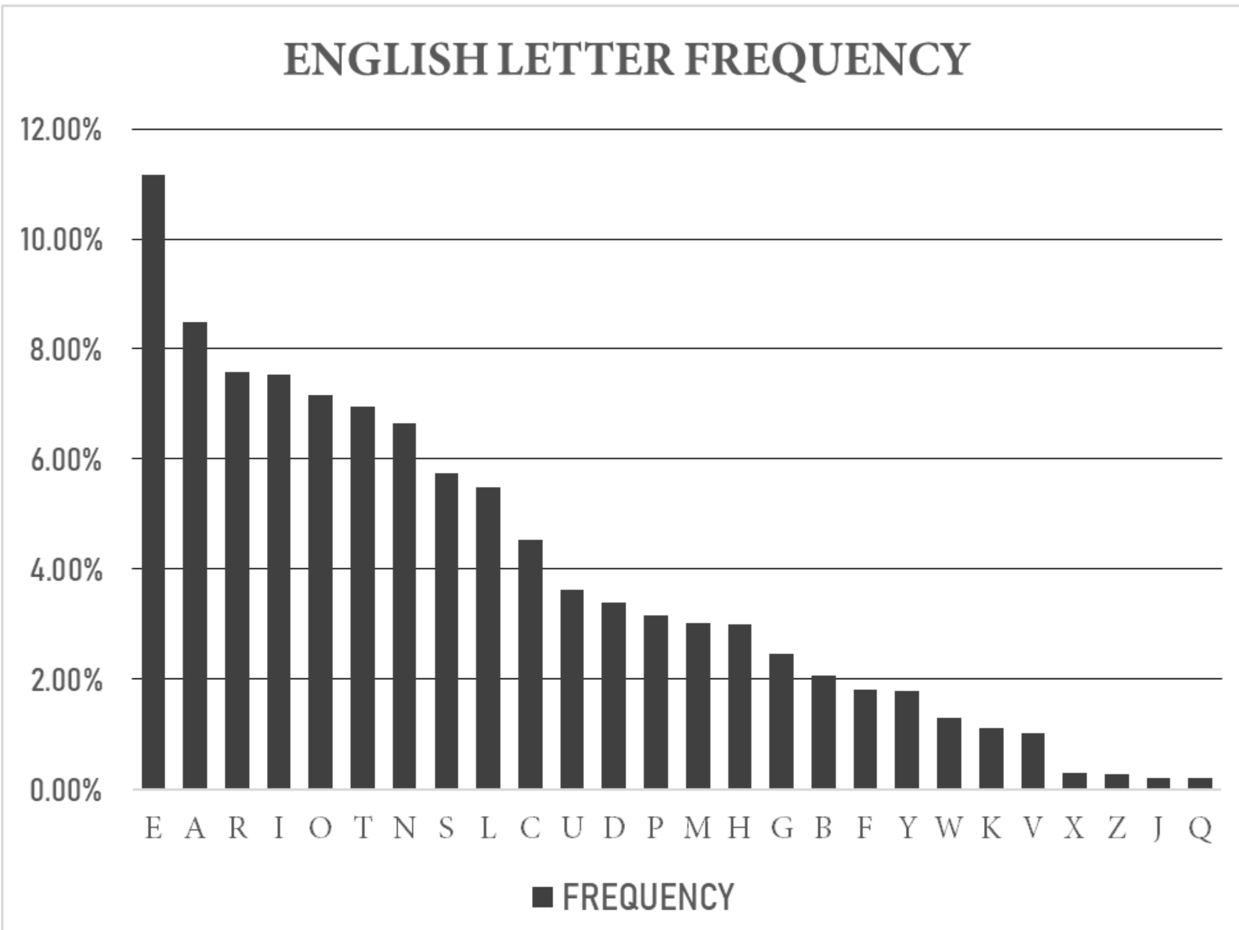
[3] ROT13 is a famous shift cipher and widely used for beginner level cryptographic problems and in CTF problems.
[4] ROT47 though more secure than ROT13 is not secure enough. It is also widely used in basic and beginner level cryptographic problems.

4.2 Cryptanalysis of Mono-Alphabetic Substitution Cipher

4.2.1 Frequency Analysis

In cryptography, frequency analysis is the study of the frequency of letters or groups of letters in a ciphertext. The method is used as an aid to breaking substitution ciphers. Example : Mono-Alphabetic Substitution Cipher, Caesar Cipher, Rotation/Shift Cipher etc. Frequency analysis consists of counting the occurrence of each letter in a text. Frequency analysis is based on the fact that, in any given piece of text, certain letters and combinations of letters occur with varying frequencies. For instance, given a section of English language, letters E, T, A and O are the most common, while letters Z, Q and X are not as frequently used.

The following chart shows the frequency of each letter of the alphabet for the English language:



We can assume that most samples of text written in English would have a similar distribution of letters. However this is only true if the sample of text is long enough. A very short text may lead to a significantly different distribution.

When trying to decrypt a cipher text based on a substitution cipher, we can use a frequency analysis to help identify the most recurring letters in a cipher text and hence make hypothesis of what these letters have been encoded as (e.g. E, T, A, O, etc.) This will help us decrypt some of the letters in the text. We can then recognise patterns/words in the partly decoded text to identify more substitutions.

4.2.2 Brute Force/Exhaustive Key Search

In cryptography, a brute-force attack consists of an attacker submitting many passwords or passphrases with the hope of eventually guessing a combination correctly. The attacker systematically checks all possible passwords and passphrases until the correct one is found. Alternatively, the attacker can attempt to guess the key which is typically created from the password using a key derivation function. This is known as an exhaustive key search.

A brute-force attack is a cryptanalytic attack that can, in theory, be used to attempt to decrypt any encrypted data (except for data encrypted in an information-theoretically secure manner). Such an attack might be used when it is not possible to take advantage of other weaknesses in an encryption system (if any exist) that would make the task easier.

4.3 Simple Substitution Cipher

It is an improvement to the Caesar Cipher. Instead of shifting the alphabets by some number, this scheme uses some permutation of the letters in alphabet. For example, A, B, . . . , Y, Z and Z, Y, . . . , A are two obvious permutation of all the letters in alphabet. Permutation is nothing but a jumbled up set of alphabets. With 26 letters in alphabet, the possible permutations are 26! (factorial of 26) which is equal to 4×10^{26}. The sender and the receiver may choose any one of these possible permutation as a ciphertext alphabet. This permutation is the secret key of the scheme.

4.3.0.1 Process of Simple Substitution Cipher

- ⋆ Take the alphabets A, B, C, . . . , Z in the natural order.
- ⋆ The sender and the receiver decide on a randomly selected permutation of the letters of the alphabet.
- ⋆ Underneath the natural order alphabets, write out the chosen permutation of the letters of the alphabet. For encryption, sender replaces each plaintext letters by substituting the permutation letter that is directly beneath it in the table. This process is shown in the following illustration. In this example, the chosen permutation is given below. The plaintext **'EXAMPLE'** is encrypted to **'TBQDHST'**.

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

- ⋆ On receiving the ciphertext, the receiver, who also knows the randomly chosen permutation, replaces each ciphertext letter on the bottom row with the corresponding plaintext letter in the top row. The ciphertext **'TBQDHST'** is decrypted to **'EXAMPLE'**.

Security Value: Simple Substitution Cipher is a considerable improvement over the Caesar Cipher. The possible number of keys is large (26!) and even the modern computing systems are not yet powerful enough to comfortably launch a brute force attack to break the system. However, the Simple Substitution Cipher has a simple design and it is prone to design flaws, say choosing obvious permutation, this cryptosystem can be easily broken.

4.4 Monoalphabetic and Polyalphabetic Cipher

Monoalphabetic cipher is a substitution cipher in which for a given key, the cipher alphabet for each plain alphabet is fixed throughout the encryption process. For example, if 'A' is encrypted as 'D', for any number of occurrence in that plaintext, 'A' will always get encrypted to 'D'.

All of the substitution ciphers we have discussed earlier in this chapter are monoalphabetic; these ciphers are highly susceptible to cryptanalysis.

Polyalphabetic Cipher is a substitution cipher in which the cipher alphabet for the plain alphabet may be different at different places during the encryption process. The next two examples, playfair and Vigenere Cipher are polyalphabetic ciphers.