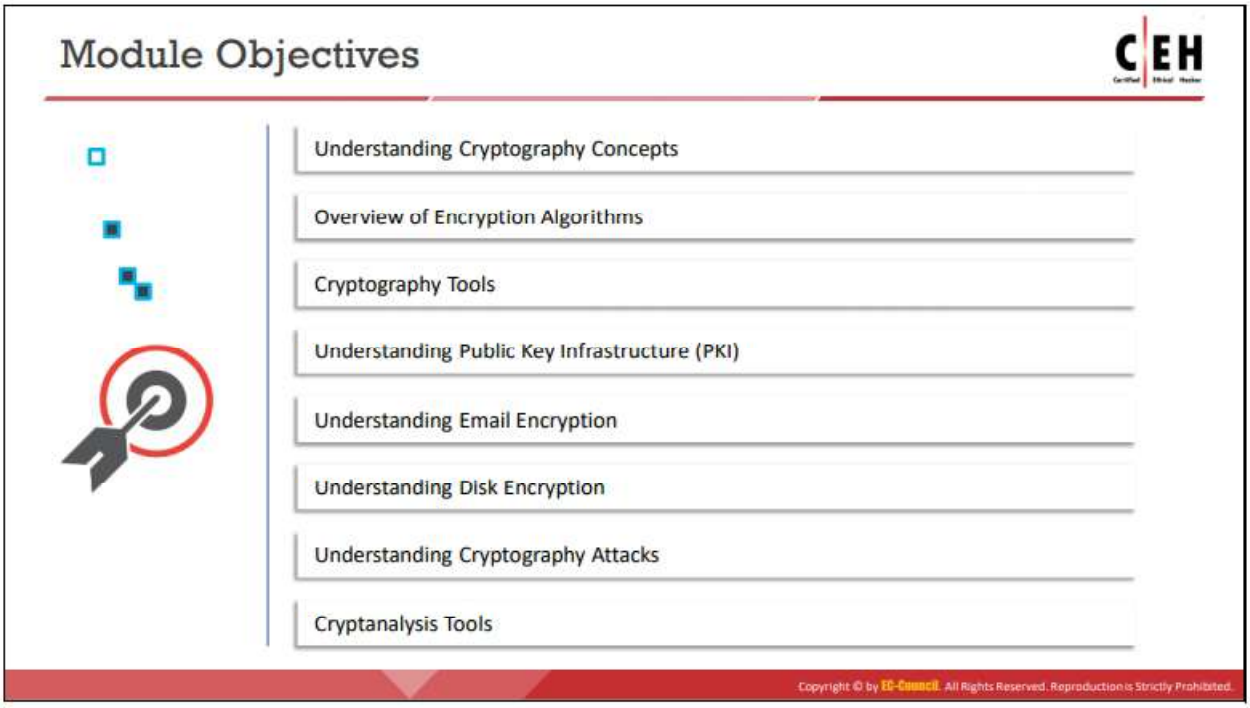
Module 20:
Cryptography



Module Objectives

With the increasing adoption of the Internet (World Wide Web) for business and personal communication, securing sensitive information such as credit card details, PINs, bank account numbers, and private messages is becoming increasingly important, albeit more difficult to achieve. Today's information-based organizations extensively use the Internet for e-commerce, market research, customer support, and a variety of other activities. Data security is critical to online business and communication privacy.

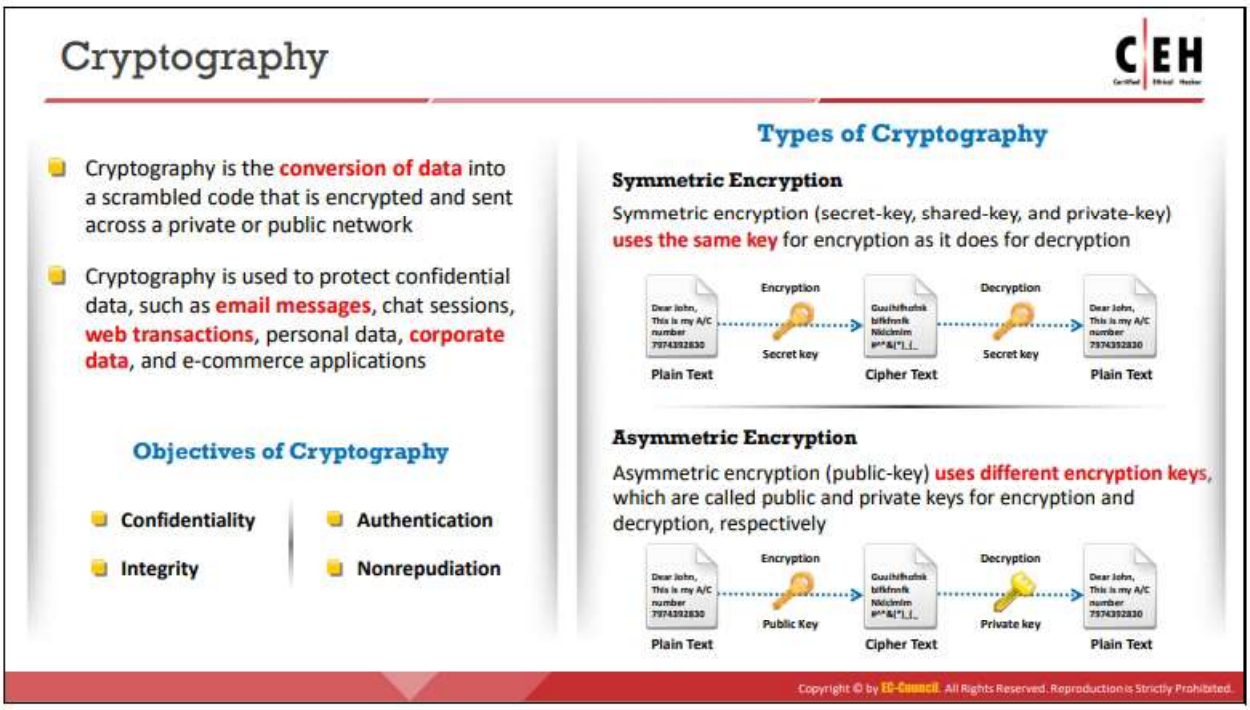
Cryptography and cryptographic ("crypto") systems help in securing data against interception and compromise during online transmissions. This module provides a comprehensive understanding of different cryptosystems and algorithms, one-way hash functions, public-key infrastructures (PKIs), and the different ways in which cryptography can ensure the privacy and security of online communication. It also covers various tools used to encrypt sensitive data.

At the end of this module, you will be able to

- Describe cryptography concepts
- Understand different encryption algorithms
- Use different cryptography tools
- Describe public key infrastructure (PKI)
- Apply email encryption
- Apply disk encryption
- Describe various cryptography attacks
- Use different cryptanalysis tools

Cryptography Concepts

Cryptography enables one to secure transactions, communications, and other processes performed in the electronic world. This section deals with cryptography and its associated concepts, which will enable you to understand the advanced topics covered later in this module.



Cryptography

"Cryptography" comes from the Greek words ***kryptos***, meaning "concealed, hidden, veiled, secret, or mysterious," and ***graphia***, meaning "writing"; thus, cryptography is "the art of secret writing."

Cryptography is the practice of concealing information by converting plaintext (readable format) into ciphertext (unreadable format) using a key or encryption scheme. It is the process of converting data into a scrambled code that is encrypted and sent across a private or public network. Cryptography protects confidential data such as email messages, chat sessions, web transactions, personal data, corporate data, e-commerce applications, and many other types of communication. Encrypted messages can, at times, be decrypted by cryptanalysis (code breaking), even though modern encryption techniques are virtually unbreakable.

Objectives of Cryptography

- **Confidentiality**: Assurance that the information is accessible only to those authorized to access it.
- **Integrity**: Trustworthiness of data or resources in terms of preventing improper and unauthorized changes.
- **Authentication**: Assurance that the communication, document, or data is genuine.
- **Nonrepudiation**: Guarantee that the sender of a message cannot later deny having sent the message and that the recipient cannot deny having received the message.

Cryptography Process

Plaintext (readable format) is encrypted by means of encryption algorithms such as RSA, DES, and AES, resulting in a ciphertext (unreadable format) that, on reaching the destination, is decrypted into readable plaintext.

Figure 20.1: Example of Cryptography

Types of Cryptography

Cryptography is categorized into two types according to the number of keys employed for encryption and decryption:

- **Symmetric Encryption**

  Symmetric encryption requires that both the sender and the receiver of the message possess the same encryption key. The sender uses a key to encrypt the plaintext and sends the resultant ciphertext to the recipient, who uses the same key (used for encryption) to decrypt the ciphertext into plaintext. Symmetric encryption is also known as secret-key cryptography, as it uses only one secret key to encrypt and decrypt the data. This type of cryptography works well when you are communicating with only a few people.

  Because the sender and receiver must share the key before sending any messages, this technique is of limited use for the Internet, where individuals who have not had prior contact frequently require a secure means of communication. The solution to this problem is asymmetric encryption (public-key cryptography).

Figure 20.2: Symmetric Encryption

- **Asymmetric Encryption**

  The concept of asymmetric encryption (also known as public-key cryptography) was introduced to solve key-management problems. Asymmetric encryption involves both a public key and a private key. The public key is publicly available, whereas the sender keeps the private key secret.

  An asymmetric-key system is an encryption method that uses a key pair comprising a public key available to anyone and a private key held only by the key owner, which helps to provide confidentiality, integrity, authentication, and nonrepudiation in data management.

Asymmetric encryption uses the following sequence to send a message:

1. An individual finds the public key of the person he or she wants to contact in a directory.
2. This public key is used to encrypt a message that is then sent to the intended recipient.
3. The receiver uses the private key to decrypt the message and reads it.

No one but the holder of the private key can decrypt a message encrypted with the corresponding public key. This increases the security of the information because all communications involve only public keys; the message sender never transmits or shares the private keys. The sender must link public keys with usernames in a secure manner to ensure that individuals claiming to be the intended recipient do not intercept the information. To meet the need for authentication, one can use digital signatures.

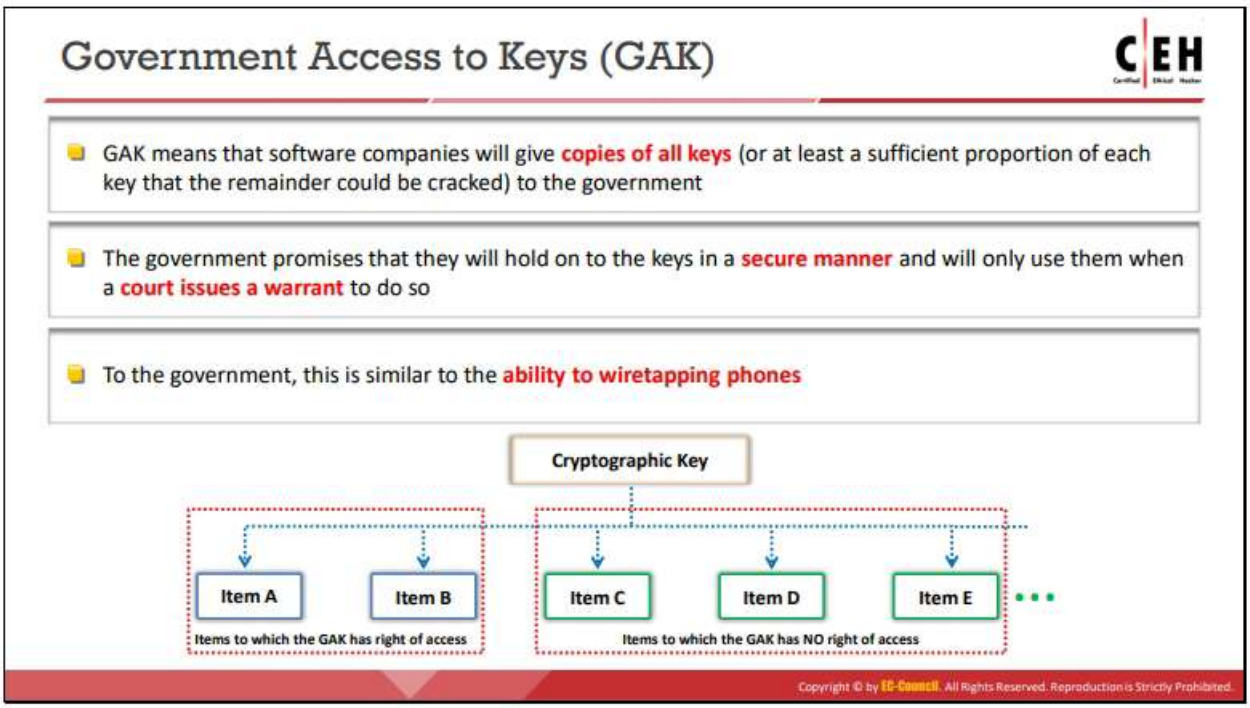
Figure 20.3: Asymmetric Encryption

Strengths and Weaknesses of Crypto Methods

	Symmetric Encryption	Asymmetric Encryption
Strengths	Faster and easier to implement, as the same key is used to encrypt and decrypt data Requires less processing power Can be implemented in application-specific integrated chip (ASIC).	Convenient to use, as the distribution of keys to encrypt messages is not required
	Prevents widespread message security compromise as different secret keys are used to communicate with different parties	Enhanced security, as one need not share or transmit private keys to anyone
	The key is not bound to the data being transferred on the link; therefore, even if the data are intercepted, it is not possible to decrypt it	Provides digital signatures that cannot be repudiated
Weaknesses	**Symmetric Encryption**	**Asymmetric Encryption**
	Lack of secure channel to exchange the secret key	Slow in processing and requires high processing power

	Difficult to manage and secure too many shared keys that are generated to communicate with different parties	Widespread message security compromise is possible (i.e., an attacker can read complete messages if the private key is compromised)
	Provides no assurance about the origin and authenticity of a message, as the same key is used by both the sender and the receiver	Messages received cannot be decrypted if the private key is lost
	Vulnerable to dictionary attacks and brute-force attacks	Vulnerable to man-in-the-middle and brute-force attacks

Table 20.1: Strengths and weaknesses of crypto methods



Government Access to Keys (GAK)

Government Access to Keys (GAK) refers to the statutory obligation of individuals and organizations to disclose their cryptographic keys to government agencies. It means that software companies will give copies of all keys (or at least enough of the key such that the remainder can be cracked) to the government. Law enforcement agencies around the world acquire and use these cryptographic keys to monitor suspicious communication and collect evidence of cybercrimes in the interests of national security. The government promises that it will hold on to the keys in a secure manner and only use them when a court issues a warrant to do so. To the government, this issue is similar to the ability to wiretap phones.

Government agencies often use key escrow for uninterrupted access to keys. Key escrow is a key exchange arrangement in which essential cryptographic keys are stored with a third party in escrow. The third party can use or allow others to use the encryption keys under certain predefined circumstances. The third party, with regard to GAK, is generally a government agency that may use the encryption keys to decipher digital evidence under authorization or a warrant from a court of law. However, there is growing concern about the privacy and security of cryptographic keys and information. Government agencies are responsible for protecting these keys. Such agencies generally use a single key to protect other keys, which is not a good idea, as revealing a single key could expose the other keys.

These agencies are not aware of how confidential the information protected by the keys is, which makes it difficult to judge how much protection is required. In cases where seized keys also protect other information that these agencies have no right to access, the consequences of key revelation cannot be determined, because government agencies are not aware of the information that the keys protect. In such cases, the key owner is liable for the consequences of key revelation. Before owners hand over their keys to government agencies, they need to be

assured that the government agencies will protect these keys according to a sufficiently strong standard to protect their interests.

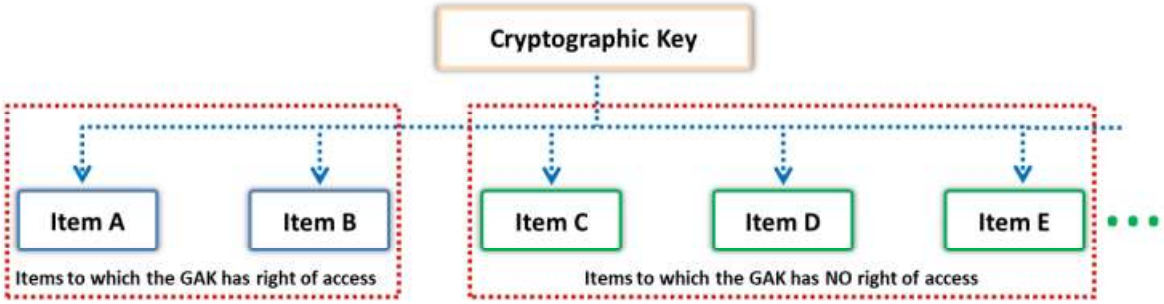
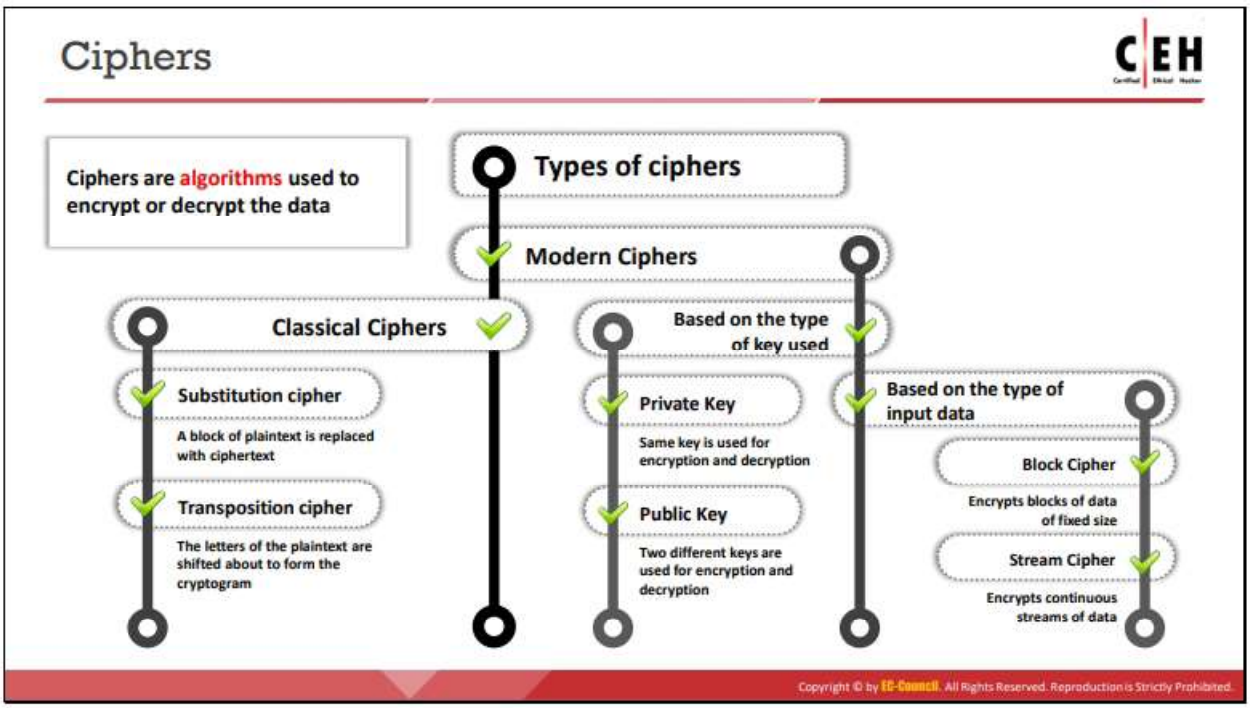


Figure 20.4: Illustration of GAK

Encryption Algorithms

Encryption is the process of converting readable plaintext into an unreadable ciphertext using a set of complex algorithms that transform the data into blocks or streams of random alphanumeric characters. This section deals with ciphers and various encryption algorithms such as DES, AES, RC4, RC5, RC6, DSA, RSA, MD5, SHA, etc.



Ciphers

In cryptography, a cipher is an algorithm (a series of well-defined steps) for performing encryption and decryption. Encipherment is the process of converting plaintext into a cipher or code; the reverse process is called decipherment. A message encrypted using a cipher is rendered unreadable unless its recipient knows the secret key required to decrypt it. Communication technologies (e.g., Internet, cell phones) rely on ciphers to maintain both security and privacy. Cipher algorithms may be open-source (the algorithmic process is in the public domain while the key is selected by a user and is private) or closed-source (the process is developed for use in specific domains, such as the military, and the algorithm itself is not in the public domain). Furthermore, ciphers may be free for public use or licensed.

Types of ciphers

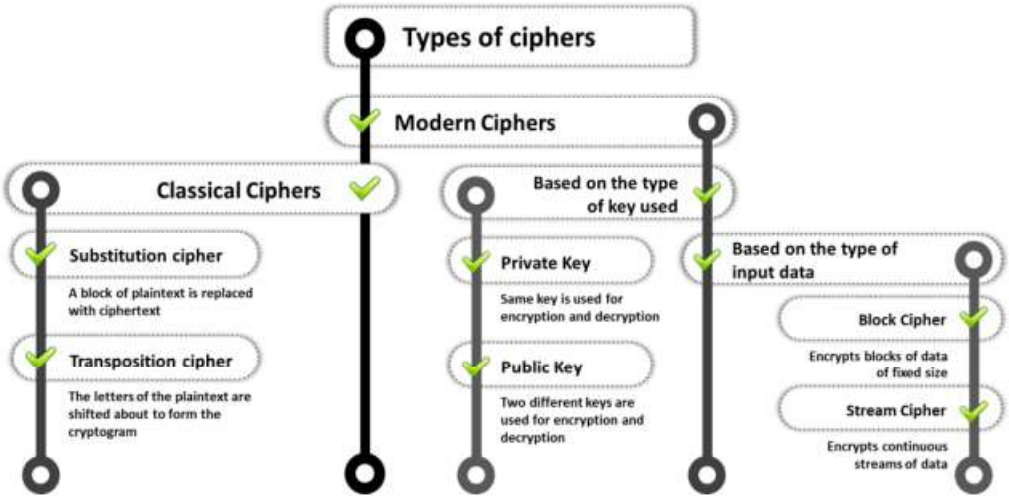


Figure 20.5: Classification of ciphers

Ciphers are of two main types: classical and modern.

- **Classical Ciphers**

  Classical ciphers are the most basic type of ciphers, which operate on letters of the alphabet (A–Z). These ciphers are generally implemented either by hand or with simple mechanical devices. Because these ciphers are easily deciphered, they are generally unreliable.

  Types of classical ciphers

  - **Substitution cipher**: The user replaces units of plaintext with ciphertext according to a regular system. The units may be single letters, pairs of letters, or combinations of them, and so on. The recipient performs inverse substitution to decipher the text. Examples include the Beale cipher, autokey cipher, Gronsfeld cipher, and Hill cipher.

    For example, "**HELLO WORLD**" can be encrypted as "**PSTER HGFST**" (i.e., H=P, E=S, etc.).

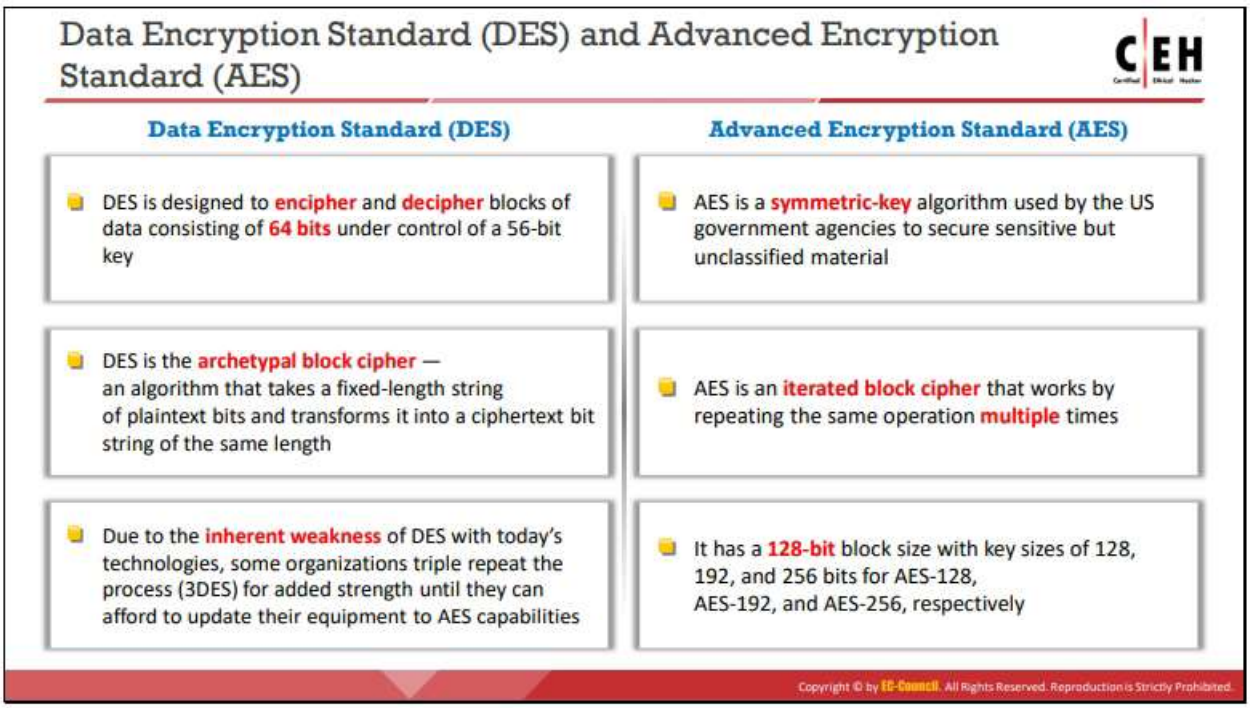
  - **Transposition cipher**: Here, letters in the plaintext are rearranged according to a regular system to produce the ciphertext. For example, "**CRYPTOGRAPHY**" when encrypted becomes "**AOYCRGPTYRHP**." Examples include the rail fence cipher, route cipher, and Myszkowski transposition.

- **Modern Ciphers**

  Modern ciphers are designed to withstand a wide range of attacks. They provide message secrecy, integrity, and authentication of the sender. A user can calculate a modern cipher using a one-way mathematical function that is capable of factoring large prime numbers.

  Types of Modern ciphers

  - **Based on the type of key used**
    - **Symmetric-key algorithms (Private-key cryptography)**: Use the same key for encryption and decryption.
    - **Asymmetric-key algorithms (Public-key cryptography)**: Use two different keys for encryption and decryption.
  - **Based on the type of input data**
    - **Block cipher**: Deterministic algorithms operating on a block (a group of bits) of fixed size with an unvarying transformation specified by a symmetric key. Most modern ciphers are block ciphers. They are widely used to encrypt bulk data. Examples include DES, AES, IDEA, etc. When the block size is less than that used by the cipher, padding is employed to achieve a fixed block size.
    - **Stream cipher**: Symmetric-key ciphers are plaintext digits combined with a key stream (pseudorandom cipher digit stream). Here, the user applies the key to each bit, one at a time. Examples include RC4, SEAL, etc.



Data Encryption Standard (DES)

DES is a standard for data encryption that uses a secret key for both encryption and decryption (symmetric cryptosystem). DES uses a 64-bit secret key, of which 56 bits are generated randomly and the other 8 bits are used for error detection. It uses a data encryption algorithm (DEA), a secret key block cipher employing a 56-bit key operating on 64-bit blocks. DES is the archetypal block cipher—an algorithm that takes a fixed-length string of plaintext bits and transforms it into a ciphertext bit string of the same length. The design of DES allows users to implement it in hardware and use it for single-user encryption, such as to store files on a hard disk in encrypted form.

DES provides 72 quadrillion or more possible encryption keys and chooses a random key for the encryption of each message. Because of the inherent weakness of DES vis-à-vis today's technologies, some organizations use triple DES (3DES), in which they repeat the process three times for added strength until they can afford to update their equipment to AES capabilities.

Triple Data Encryption Standard (3DES)

Eventually, it became obvious that DES would no longer be secure. The U.S. Federal Government began a contest seeking a replacement cryptography algorithm. However, in the meantime, 3DES was created as an interim solution. Essentially, it performs DES three times with three different keys. 3DES uses a "key bundle" that comprises three DES keys, K1, K2, and K3. Each key is a standard 56-bit DES key. It then performs the following process:

DES *encrypt* with K1, DES *decrypt* with K2, DES *encrypt* with K3

There are three options for the keys. In the first option, all three keys are independent and different. In the second option, K1 and K3 are identical. In the third option, all three keys are the same; therefore, you are literally applying the same DES algorithm three times with the same key. The first option is the most secure, while the third is the least secure.

Advanced Encryption Standard (AES)

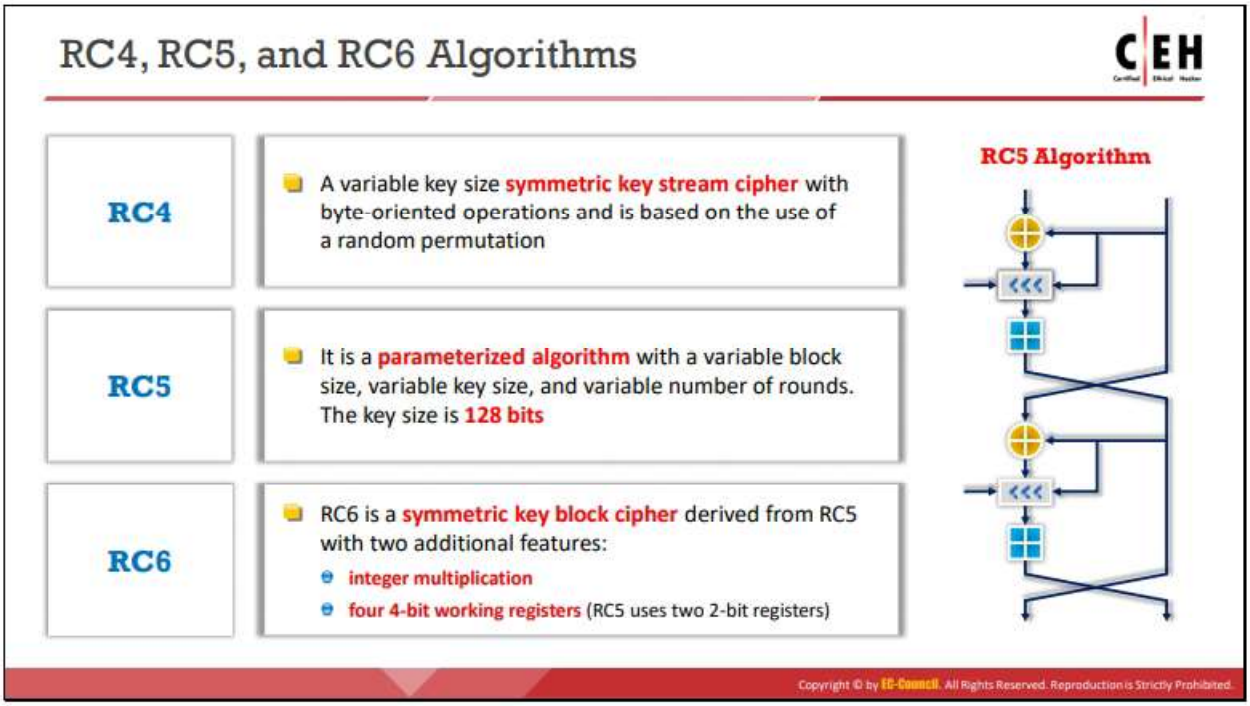
The Advanced Encryption Standard (AES) is a National Institute of Standards and Technology (NIST) specification for the encryption of electronic data. It also helps to encrypt digital information such as telecommunications, financial, and government data. US government agencies have been using it to secure sensitive but unclassified material.

AES consists of a symmetric-key algorithm: both encryption and decryption are performed using the same key. It is an iterated block cipher that works by repeating the defined steps multiple times. It has a 128-bit block size, with key sizes of 128, 192, and 256 bits for AES-128, AES-192, and AES-256, respectively. The design of AES makes its use efficient in both software and hardware. It works simultaneously at multiple network layers.

AES Pseudocode

Initially, the system copies the cipher input into the internal state and then adds an initial round key. The system transforms the state by iterating a round function in a number of cycles. The number of cycles may vary with the block size and key length. After completing rounding, the system copies the final state into the cipher output.

```
Cipher (byte in [4*Nb], byte out [4*Nb], word w[Nb*(Nr+1)])
begin
  byte state[4, Nb]
  state = in
  AddRoundKey (state, w)
    for round = 1 step 1 to Nr-1
       SubBytes(state)
       ShiftRows(state)
       MixColumns(state)
       AddRoundKey(state, w+round*Nb)
    end for
  SubBytes(state)
  ShiftRows(state)
  AddRoundKey(state, w+Nr*Nb)
  out = state
end
```



RC4, RC5, and RC6 Algorithms

Symmetric encryption algorithms developed by RSA Security are discussed below.

- **RC4**

  RC4 is a variable key-size symmetric-key stream cipher with byte-oriented operations, and it is based on the use of a random permutation. According to some analyses, the period of the cipher is likely to be greater than 10,100. Each output byte uses 8 to 16 system operations; thus, the cipher can run fast when used in software. RC4 enables safe communications such as for traffic encryption (which secures websites) and for websites that use the SSL protocol.

- **RC5**

  RC5 is a fast symmetric-key block cipher designed by Ronald Rivest for RSA Data Security (now RSA Security). The algorithm is a parameterized algorithm with a variable block size, a variable key size, and a variable number of rounds. The block sizes can be 32, 64, or 128 bits. The range of the rounds can vary from 0 to 255, and the size of the key can vary from 0 to 2,040 bits. This built-in variability can offer flexibility at all levels of security. The routines used in RC5 are key expansion, encryption, and decryption.

  In the key expansion routine, the secret key that a user provides is expanded to fill the key table (the size of which depends on the number of rounds). RC5 uses a key table for both encryption and decryption. The encryption routine has three fundamental operations: integer addition, bitwise XOR, and variable rotation. The intensive use of data-dependent rotation and the combination of different operations make RC5 a secure encryption algorithm.

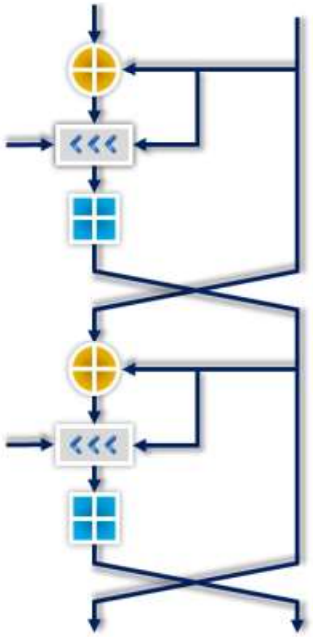


Figure 20.6: Block diagram of the RC5 algorithm

- **RC6**

  RC6 is a symmetric-key block cipher derived from RC5. It is a parameterized algorithm with a variable block size, key size, and number of rounds. Two features that differentiate RC6 from RC5 are integer multiplication (which is used to increase the diffusion, achieved in fewer rounds with increased speed of the cipher) and the use of four 4-bit working registers rather than two 2-bit registers. RC6 uses four 4-bit registers instead of two 2-bit registers because the block size of the AES is 128 bits.

Blowfish

Blowfish is a type of symmetric block cipher algorithm designed to replace DES or IDEA algorithms. It uses the same secret key to encrypt and decrypt data. This algorithm splits the data into a block length of 64 bits and produces a key ranging from 32 bits to 448 bits. Due to its high speed and overall efficiency, blowfish is used in software ranging from password protection tools to e-commerce websites for securing payments.

It is a 16-round Feistel cipher working on 64-bit blocks. However, unlike DES, its key size ranges from 32 bits to 448 bits.

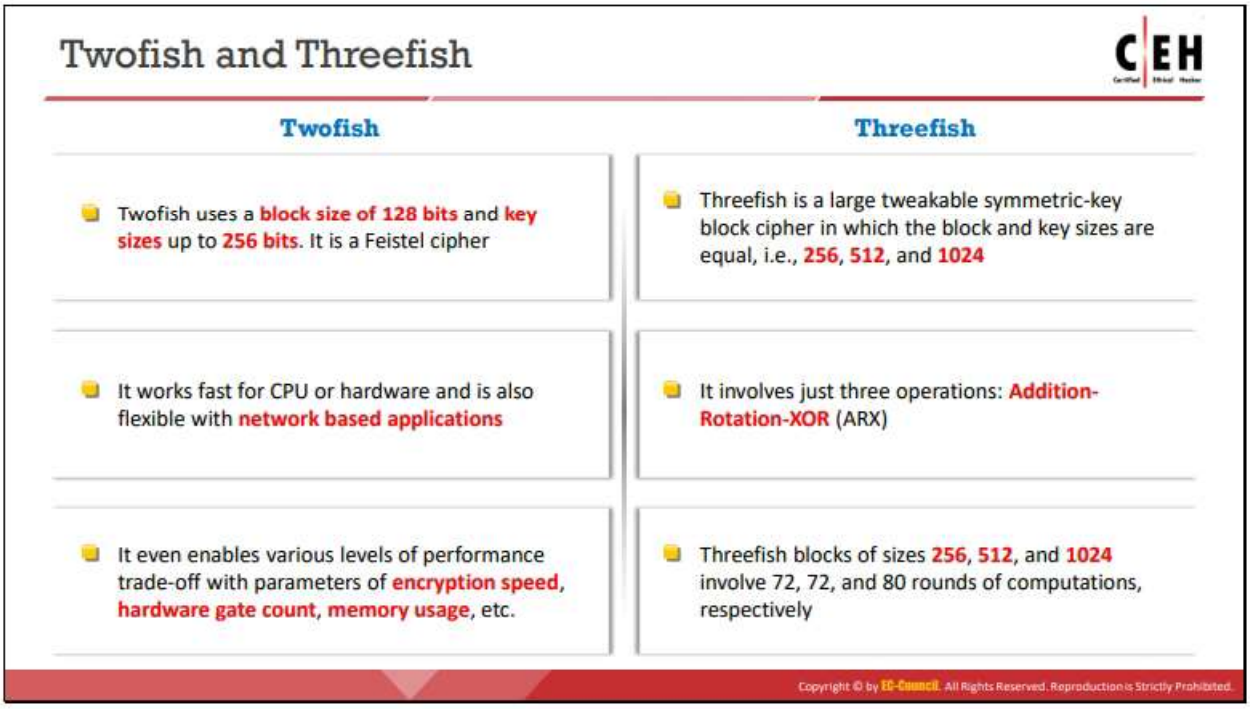
This algorithm has two parts. The first part handles the expansion of the key. The second part actually encrypts the data.

The key expansion is handled in several steps. The first step is to break the original key into a set of subkeys. Specifically, a key of no more than 448 bits is separated into 4,168 bytes. There is a P-array and four 32-bit S-boxes. The P-array contains 18 32-bit subkeys, while each S-box contains 256 entries.

Key expansion is performed as follows:

1. The first step is to initialize the **P-array** and **S-boxes**.
2. Then, XOR the P-array with the key bits. For example, **P1 XOR** (first 32 bits of the key), **P2 XOR** (next 32 bits of the key).
3. Use the above method to encrypt the **all-zero string**.
4. This new output is now P1 and P2.
5. Encrypt the new P1 and P2 with the **modified subkeys**.
6. This new output is now P3 and P4.
7. Repeat the process **521 times** to calculate new subkeys for the P-array and the four S-boxes.

The round function splits the 32-bit input into four 8-bit quarters and uses the quarters as input to the S-boxes. The outputs are added modulo **232** and **XORed** to produce the final **32-bit output**.



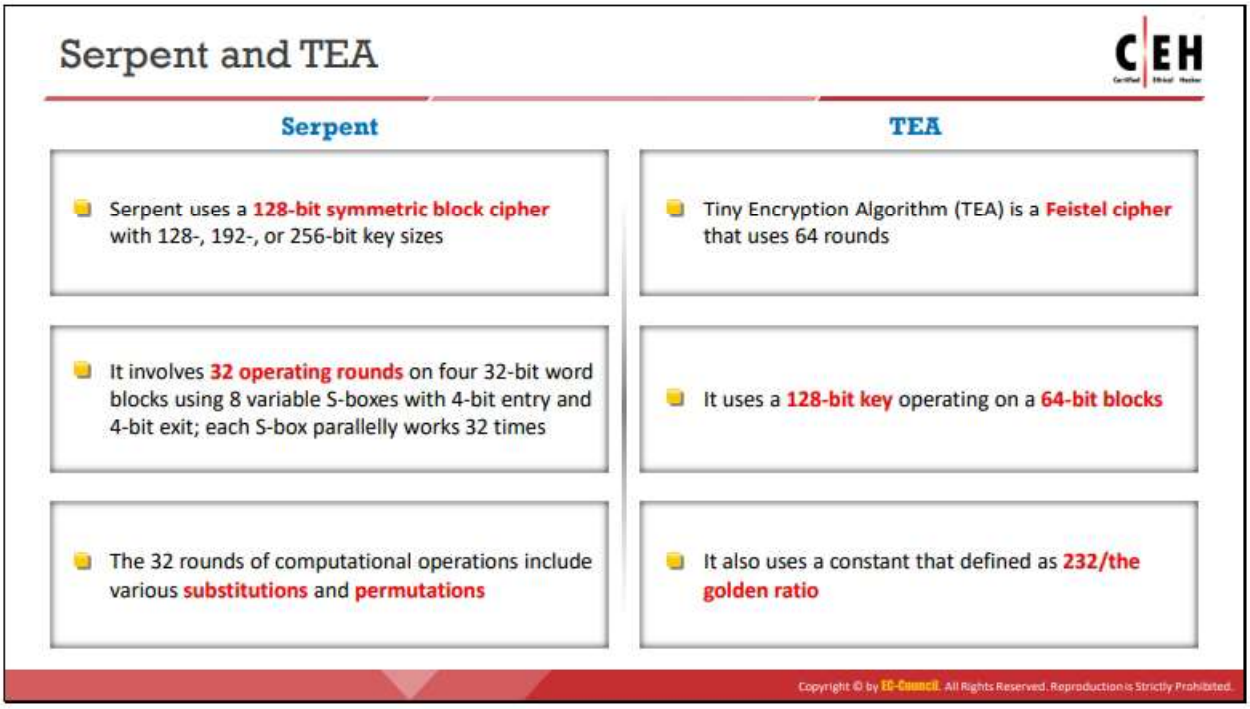
Twofish

The Twofish algorithm was one of the U.S. Government's five finalists to replace DES, but it was not chosen. It was designed by Bruce Schneier, John Kelsey, Doug Whiting, David Wagner, Chris Hall, and Niels Ferguson.

TwoFish is a 128-bit block cipher. It is one of the most conceptually simple algorithms that uses a single key for both encryption and decryption for any length up to 256 bits. It is a Feistel cipher. It not only works fast for CPU or hardware but is also flexible for network-based applications. Furthermore, it allows various levels of performance trade-off on parameters such as encryption speed, hardware gate count, memory usage, etc. This technique of enabling different implementations improves the relative performance of the algorithm. Any user can optimize the performance based on the key scheduling.

Threefish

Threefish was developed in 2008 and it is a part of the Skein algorithm. It was enrolled in NIST's SHA-3 (hash function) contest. It is a large tweakable symmetric-key block cipher in which the block and key sizes are equal, i.e., 256, 512, and 1024. Threefish involves only three operations, i.e., ARX (addition-rotation-XOR), which makes the coding simple, and all these operations work on 64-bit words. Threefish blocks 256, 512, and 1024 involve 72, 72, and 80 rounds of computations, respectively, to achieve the final security goal. This algorithm does not use S-boxes to prevent cache timing attacks.



Serpent

Like Blowfish, Serpent is a symmetric-key block cipher that was a finalist in the AES contest. This algorithm was designed by Ross Anderson, Eli Biham, and Lars Knudsen. It uses a 128-bit symmetric block cipher with key sizes of 128, 192, or 256 bits. It can be integrated into software or hardware programs without any restrictions.

Serpent involves 32 rounds of computational operations that include substitution and permutation operations on four 32-bit word blocks using 8-variable S-boxes with 4-bit entry and 4-bit exit. All S-boxes work parallelly 32 times. Although, Serpent is one of the most secure encryption mechanisms in AES contests, researchers have chosen Rijndael over Serpent due to its moderate encryption speed (owing to the number of rounds it uses) and complexity. Serpent minimizes the correlation between encoded images or plaintexts to a greater extent compared to Twofish and Rijndael. Therefore, Rijndael is the stand-out AES competitor and is now being used as AES.

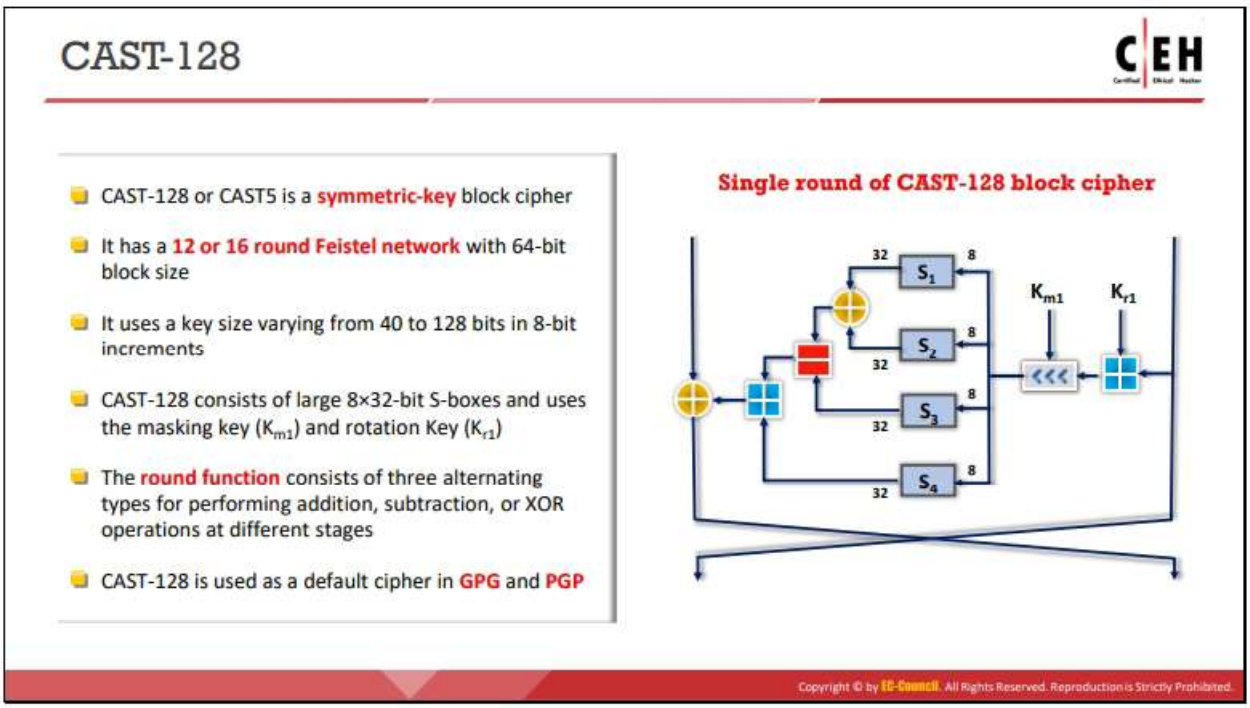
TEA

The tiny encryption algorithm (TEA) was created by David Wheeler and Roger Needham, and it was publicly presented for the first time in 1994. It is a simple algorithm, easy to implement in code. It is a Feistel cipher that uses 64 rounds (note that this is a suggestion; it can be implemented with fewer or more rounds). The number of rounds should be even since they are implemented in pairs called cycles.

TEA uses a 128-bit key operating on a 64-bit block. It also uses a constant that is defined as 232/the golden ratio. This constant is referred to as delta, and in each round, a multiple of delta is used. The 128-bit key is split into four different 32-bit subkeys labeled K[0], K[1], K[2], and K[3].

Instead of using the XOR operation, TEA uses addition and subtraction, but with mod 232. The block is divided into two halves, R and L. R is processed through the round function.

The round function takes the R half and performs a left shift of 4. Then, the result of this operation is added to K[0]. Next, the result of this operation is added to delta (recall that delta is the current multiple of 232/the golden ratio). The result of this operation is then shifted right by 5 and added to K[1]. This is the round function. As with all Feistel ciphers, the result of the round function is XORed with L, and L and R are then swapped for the next round.



CAST-128

CAST-128, also called CAST5, is a symmetric-key block cipher having a classical 12- or 16-round Feistel network with a block size of 64 bits. CAST-128 uses a key size varying from 40 bits to 128 bits in 8-bit increments. The CAST-128 components include large 8×32-bit S-boxes (S1, S2, S3, S4) based on bent functions, modular addition and subtraction, key-dependent rotation, and XOR operations. CAST-128 uses a masking key (K_{m1}) and a rotation key (K_{r1}) for performing its functions. The round function consists of three alternating types to perform addition, subtraction, or XOR operations in different stages. It used as a default cipher in GPG (GNU Privacy Guard) and PGP (Pretty Good Privacy).

CAST-256 is an extension of CAST-128 that uses the same design procedure. CAST-256 has a 128-bit block size, and it uses key sizes varying from 128 to 256 bits. Furthermore, it uses zero-correlation cryptanalysis, which can break 28 rounds with time = 2246.9 and data = 298.8.

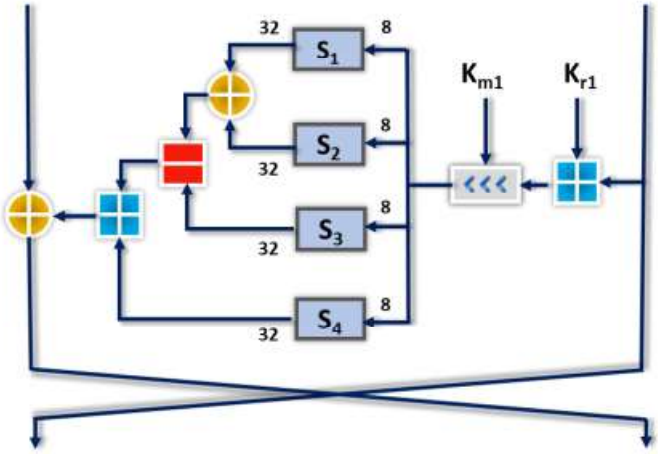
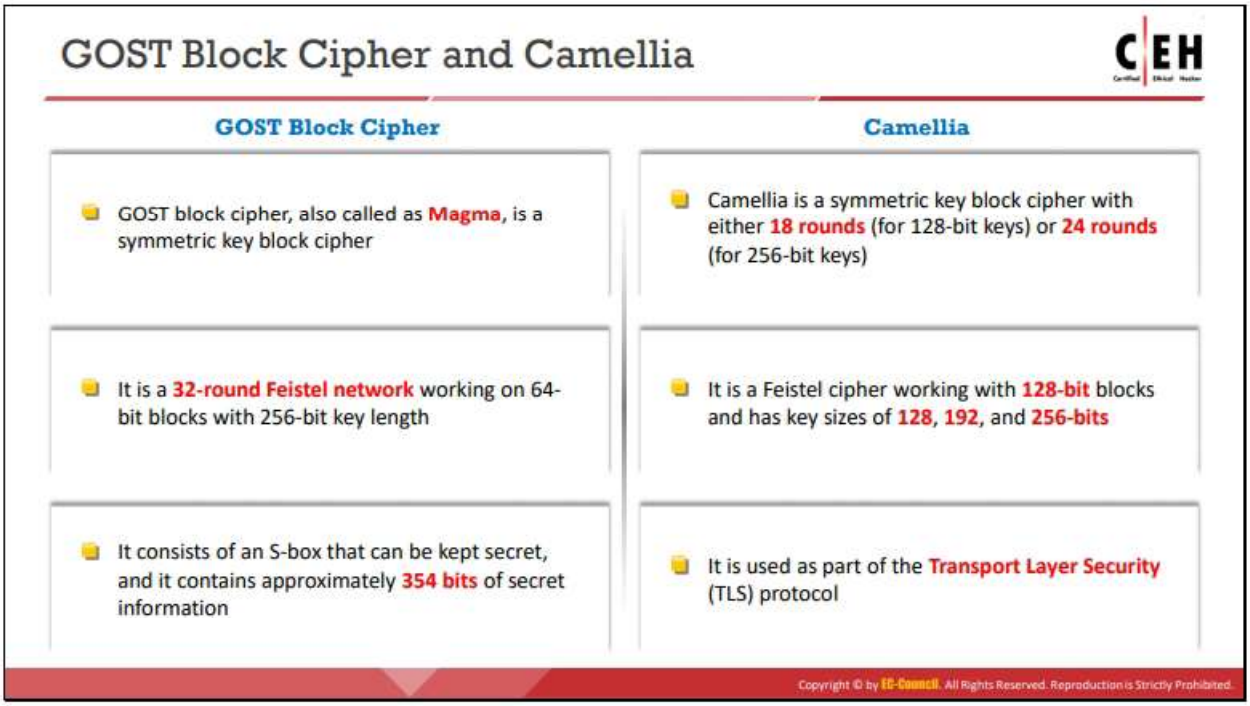


Figure 20.7: Block diagram of CAST-128



GOST Block Cipher

The GOST (Government Standard) block cipher, also called Magma, is a symmetric-key block cipher having a 32-round Feistel network working on 64-bit blocks with a 256-bit key length. It consists of an S-box that can be kept secret and it contains around 354 bits of secret information. GOST is a simple encryption algorithm, where the round function 32-bit subkey modulo 232 is added and put in the layer of S-boxes and the rotate left shift operation is used for shifting 11 bits, thereby providing the output of the round function.

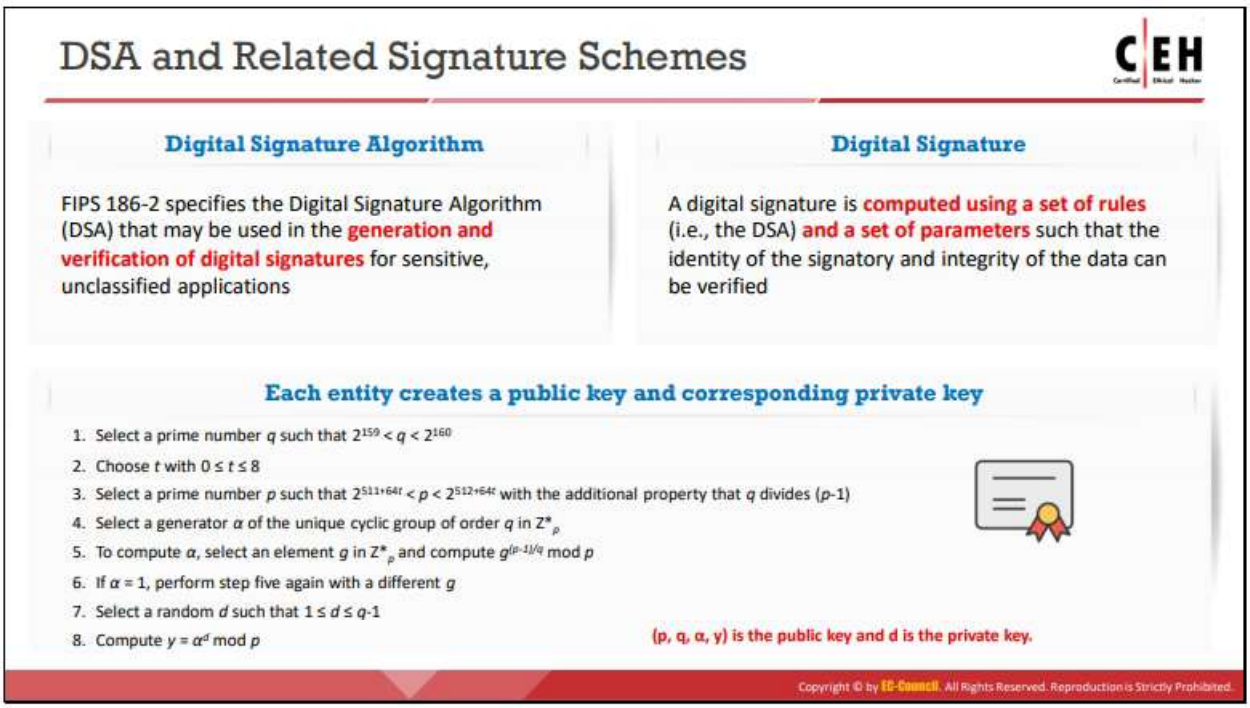
The key scheduling of the GOST block cipher is performed by breaking the 256-bit key into eight 32-bit subkeys, where each subkey is used four times. In this algorithm, the key words are used in order for the first 24 rounds and they are used in reverse order for the last 8 rounds.

Kuznyechik is the latest extension of GOST, which uses 128-bit blocks.

Camellia

Camellia is a symmetric-key block cipher having either 18 rounds (for 128-bit keys) or 24 rounds (for 256-bit keys). It is a Feistel cipher with a block size of 128 bits and a key size of 128, 192, and 256 bits. Camellia uses four 8×8-bit S-boxes that perform affine transformations and logical operations. A logical transformation layer FL-function or its inverse is applied every six rounds. Camellia uses the key whitening technique for increased security.

Camellia is a part of the Transport Layer Security (TLS) protocol, which is used to deliver secure communication. Camellia cannot be brute-forced even with the latest technology although it uses a smaller key size of 128 bits, thus making it a safe cipher. In addition, Camellia offers high security and its processing skills are equivalent to those of AES or Rijndael.



DSA and Related Signature Schemes

The Digital Signature Algorithm (DSA) is a Federal Information Processing Standard for digital signatures. The NIST proposed the DSA for use in the Digital Signature Standard (DSS), adopted as FIPS 186. The DSA helps in the generation and verification of digital signatures for sensitive and unclassified applications. It creates a 320-bit digital signature with 512–1024-bit security.

A digital signature is a mathematical scheme used for the authentication of digital messages. Computation of the digital signature uses a set of rules (i.e., the DSA) and a set of parameters in that the user can verify the identity of the signatory and the integrity of the data.

Processes involved in DSA:

- **Signature Generation Process**: The private key is used to know who has signed it.
- **Signature Verification Process**: The public key is used to verify whether the given digital signature is genuine.

DSA is a public-key cryptosystem, as it involves the use of both private and public keys.

Benefits of DSA:

- Less chances of forgery compared with a written signature
- Quick and easy method of business transactions
- Fake currency problem can be mitigated considerably

DSA Algorithm:

Each entity A does the following:

1. Select a prime number q such that $2^{159} < q < 2^{160}$

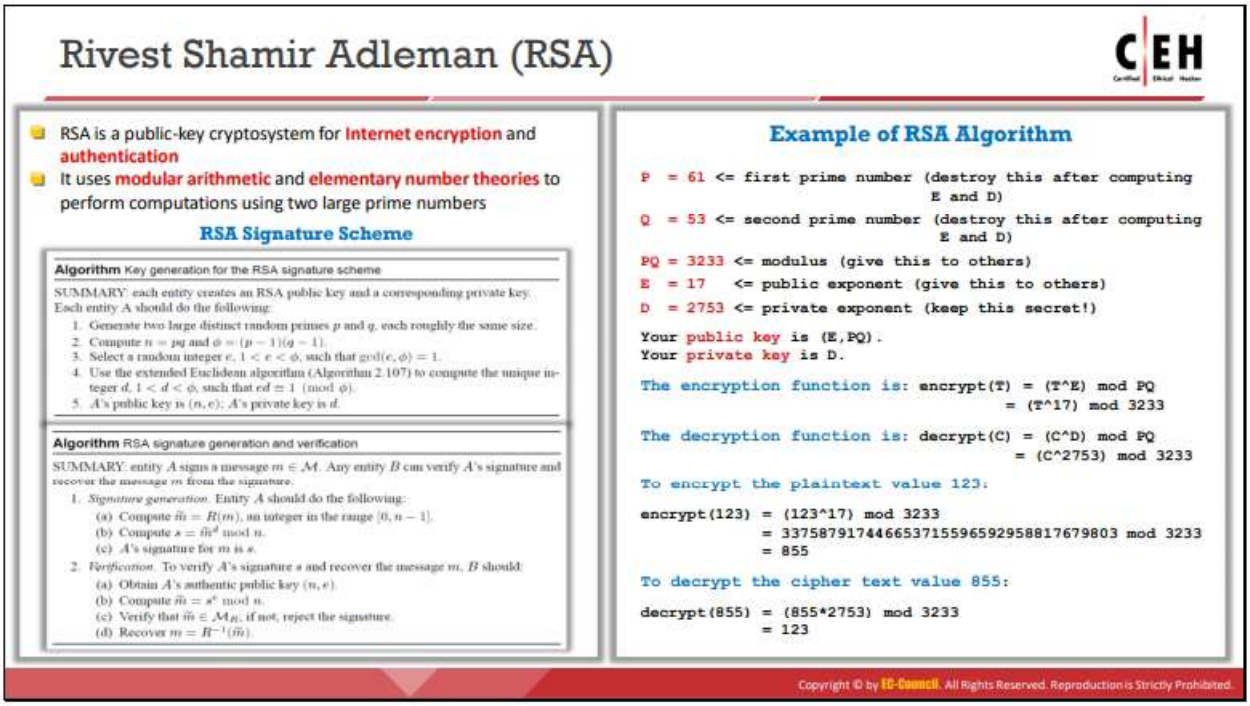
2. Choose **t** such that $0 \leq t \leq 8$, and select a prime number **p** where $2^{511+64t} < p < 2^{512+64t}$, with the property that **q** divides **(p-1)**
3. Select a generator **α** of the unique cyclic group of order **q** in Z^*_p by choosing an element $g \in Z^*_p$ and then computing $\alpha = g^{(p-1)/q} \bmod p$ until $\alpha \neq 1$
4. Select a random integer **d** such that $1 \leq d \leq q-1$
5. Compute $y = \alpha^d \bmod p$
6. A's public key is **(p, q, α, y)**; A's private key is **d**.

To sign a message **m**, A does the following:

1. Select a random secret integer **k**, $0<k<q$.
2. Compute $r=(\alpha^k \bmod p) \bmod q$
3. Compute $k^{-1} \bmod q$
4. Compute $s=k^{-1}\{h(m) + dr\} \bmod q$, where **h** is the Secure Hash Algorithm
5. A's signature for **m** is the pair **(r, s)**

To verify A's signature **(r, s)** on **m**, B should do the following:

1. Obtain A's authentic public key **(p,q,α,y)**
2. Verify that $0<r<q$ and $0<s<q$; if not, then reject the signature
3. Compute $w = s^{-1} \bmod q$ and **h(m)**
4. Compute $u_1 = w.h(m) \bmod q$ and $u_2 = rw \bmod q$
5. Compute $v = (\alpha^{u1} y^{u2} \bmod p) \bmod q$
6. Accept the signature if and only if $v=r$



Rivest Shamir Adleman (RSA)

Ron Rivest, Adi Shamir, and Leonard Adleman formulated RSA, a public-key cryptosystem for Internet encryption and authentication. RSA uses modular arithmetic and elementary number theories to perform computations using two large prime numbers. The RSA system is widely used in a variety of products, platforms, and industries. It is one of the de-facto encryption standards. Companies such as Microsoft, Apple, Sun, and Novell build RSA algorithms into their operating systems. RSA can also be found on hardware-secured telephones, Ethernet network cards, and smart cards.

RSA works as follows:

1. Two large prime numbers are taken (a and b), and their product is determined (c = ab, where "c" is called the modulus).
2. RSA chooses a number "e" that it is less than "c" and relatively prime to (a-1)(b-1). Therefore, e and (a-1)(b-1) have no common factor except 1.
3. Furthermore, RSA chooses a number "f" such that (ef - 1) is divisible by (a-1)(b-1).
4. The values "e" and "f" are the public and private exponents, respectively.
5. The public key is the pair (c, e); the private key is the pair (c, f).
6. It is difficult to obtain the private key (c, f) from the public key (c, e). However, if someone can factor "c" into "a" and "b", then that person can decipher the private key (c, f).

The security of the RSA system depends on the assumption that such factoring is difficult to carry out, making the cryptographic technique safe.

An example of how cryptography uses RSA algorithms in a practical interchange is illustrated by the following sequence:

1. The sender of a message encrypts it using a randomly chosen DES symmetric key. DES (Data Encryption Standard) is a relatively insecure symmetric-key system using 64-bit encryption (56 bits for key size, 8 bits for cyclic redundancy check) to encrypt data.
2. The sender will then look up the recipient's public key and use it to encrypt the DES key using the RSA system.
3. The sender transmits an RSA digital envelope, consisting of a DES-encrypted message and an RSA-encrypted DES key, to the recipient.
4. The recipient will decrypt the DES key and then use the DES key to decrypt the message itself.

This system combines the high speed of DES with the key management convenience of the RSA system.

RSA Signature Scheme

Cryptography uses RSA for public key encryption and for a digital signature (to sign a message and verify it). The RSA signature scheme is the first technique used to generate digital signatures. It is a deterministic digital signature scheme that provides message recovery from the signature itself, making it the most practical and versatile technique available.

RSA involves both a public key and a private key. The public key, as the name indicates, can be used by anyone for encrypting messages. The messages that the user encrypts with the public key require the private key for decryption.

Consider that John encrypts his document M using his private key S_A, thereby creating a signature $S_{john}(M)$. John sends M along with the signature $S_{john}(M)$ to Alice. Alice decrypts the document using Alice's public key, thereby verifying John's signature.

RSA Key Generation

The procedure for RSA key generation is common to all the RSA-based signature schemes. To generate an RSA key pair, i.e., both an RSA public key and the corresponding private key, each entity A should do the following:

- Generate two large distinct primes p and q arbitrarily, each with roughly the same bit length
- Compute n = pq and $\phi = (p-1)(q-1)$
- Choose a random integer e, $1 < e < \phi$,such that $\gcd(e, \phi) = 1$

  GCD = Greatest Common Divisor
- Use the extended Euclidean algorithm to compute the unique integer d, $1 < d < \phi$,such that $ed \equiv 1 \pmod{\phi}$
- A's public key is (n, e); A's private key is d

Destroy p and q at the end of the key generation

The RSA algorithm generates and verifies the RSA signature as follows way:

Entity A signs a message m∈M. Any entity B can verify A's signature and recover the message m from the signature.

1. **Signature Generation**

   To sign a message m, entity A should do the following:

   - Compute $\tilde{m} = R(m)$, an integer in the range [0, n–1]
   - Compute $s = \tilde{m}^d \bmod n$
   - A's signature form is s

2. **Signature Verification**

   To verify A's signature s and recover the message m, B should do the following:

   - Obtain A's authentic public key (n, e)
   - Compute $\tilde{m} = s^e \bmod n$
   - Verify that $\tilde{m} \in M_R$; if not, reject the signature
   - Recover $m = R^{-1}(\tilde{m})$

Example of RSA Algorithm

The math underlying RSA public-key encryption is described below:

1. Find P and Q, two large (e.g., 1024-bit) prime numbers.
2. Choose E such that E is greater than 1, E is less than PQ, and E and (P-1)(Q-1) are relatively prime, which means that they have no prime factors in common. E does not have to be prime, but it must be odd. (P-1)(Q-1) cannot be prime because it is an even number.
3. Compute D such that (DE - 1) is evenly divisible by (P-1)(Q-1). Mathematicians write this as DE = 1 (mod (P-1)(Q-1)), and they call D the multiplicative inverse of E. This is easy to do—simply find an integer X that causes D = (X(P-1)(Q-1) + 1)/E to be an integer and then use that value of D.
4. The encryption function is C = (T^E) mod PQ, where C is the ciphertext (a positive integer), T is the plaintext (a positive integer), and ^ indicates exponentiation. During the encryption of the message, T must be less than the modulus, PQ.
5. The decryption function is T = (C^D) mod PQ, where C is the ciphertext (a positive integer), T is the plaintext (a positive integer), and ^ indicates exponentiation.

Your public key is the pair (PQ, E). Your private key is the number D (do not reveal it to anyone). The product PQ is the modulus. E is the public exponent. D is the secret exponent.

You can publish your public key freely because there are no known easy methods of calculating D, P, or Q given only (PQ, E) (your public key).

Given below is an example of the RSA algorithm:

P = 61<= first prime number (destroy this after computing E and D)

Q = 53<= second prime number (destroy this after computing E and D)

PQ = 3233<= modulus (give this to others)

E = 17<= public exponent (give this to others)

D = 2753<= private exponent (keep this secret)

Your **public** key is **(E,PQ)**

Your **private** key is **D**

The encryption function is:

encrypt(T) = (T^E) mod PQ

= (T^17) mod 3233

The decryption function is:

decrypt(C) = (C^D) mod PQ

= (C^2753) mod 3233

To encrypt the plaintext value 123, do this:

encrypt(123) = (123^17) mod 3233

= 337587917446653715596592958817679803 mod 3233

= 855

To decrypt the ciphertext value 855, do this:

decrypt(855) = (855*2753) mod 3233

= 123

One way to compute the value of **855^2753 mod 3233** is as follows:

Consider these powers of 855:

- 855^1 = 855 (mod 3233)
- 855^2 = 367 (mod 3233)
- 855^4 = 367^2 (mod 3233) = 2136 (mod 3233)
- 855^8 = 2136^2 (mod 3233) = 733 (mod 3233)
- 855^16 = 733^2 (mod 3233) = 611 (mod 3233)
- 855^32 = 611^2 (mod 3233) = 1526 (mod 3233)
- 855^64 = 1526^2 (mod 3233) = 916 (mod 3233)
- 855^128 = 916^2 (mod 3233) = 1709 (mod 3233)

- 855^256 = 1709^2 (mod 3233) = 1282 (mod 3233)
- 855^512 = 1282^2 (mod 3233) = 1160 (mod 3233)
- 855^1024 = 1160^2 (mod 3233) = 672 (mod 3233)
- 855^2048 = 672^2 (mod 3233) = 2197 (mod 3233)

Given the above, we know the following:

855^2753 (mod 3233)

= 855^(1 + 64 + 128 + 512 + 2048) (mod 3233)

= 855^1 * 855^64 * 855^128 * 855^512 * 855^2048 (mod 3233)

= 855 * 916 * 1709 * 1160 * 2197 (mod 3233)

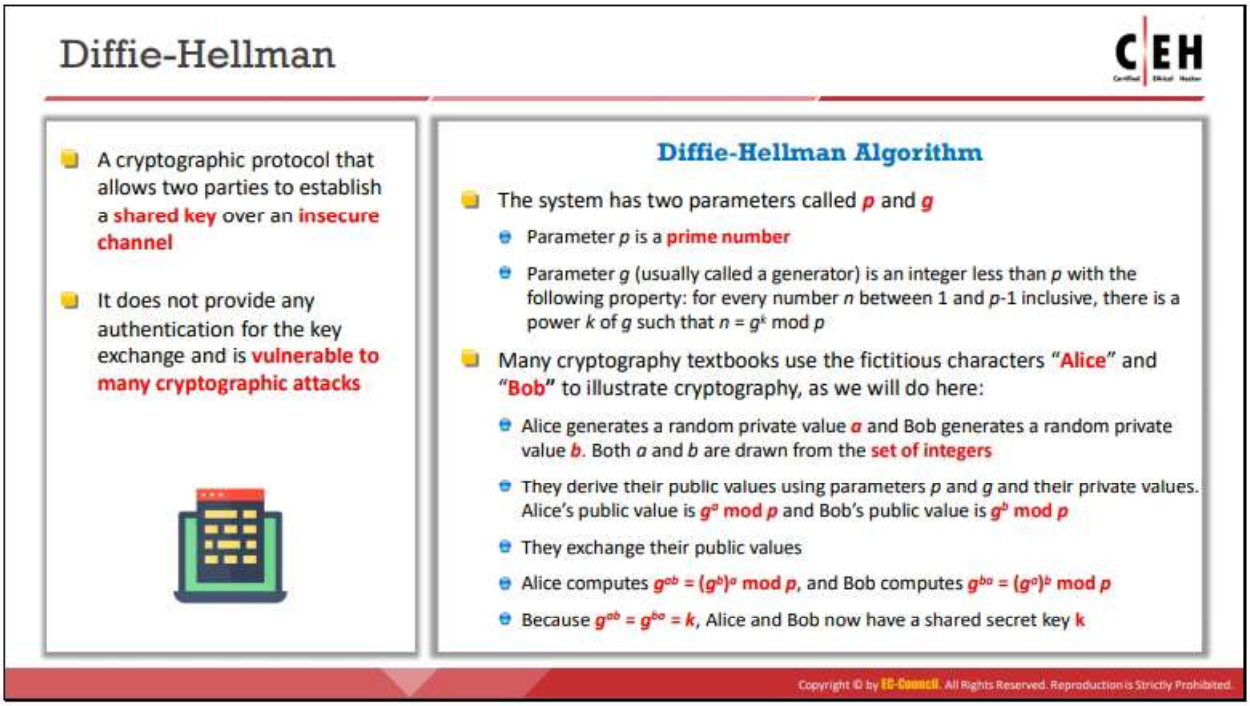
= 794 * 1709 * 1160 * 2197 (mod 3233)

= 2319 * 1160 * 2197 (mod 3233)

= 184 * 2197 (mod 3233)

= 123 (mod 3233)

= 123



Diffie–Hellman

It is a cryptographic protocol that allows two parties to establish a shared key over an insecure channel. It was developed and published by Whitfield Diffie and Martin Hellman in 1976. Actually, it was independently developed a few years earlier by Malcolm J. Williamson of the British Intelligence Service, but it was classified at that time.

Diffie–Hellman Algorithm

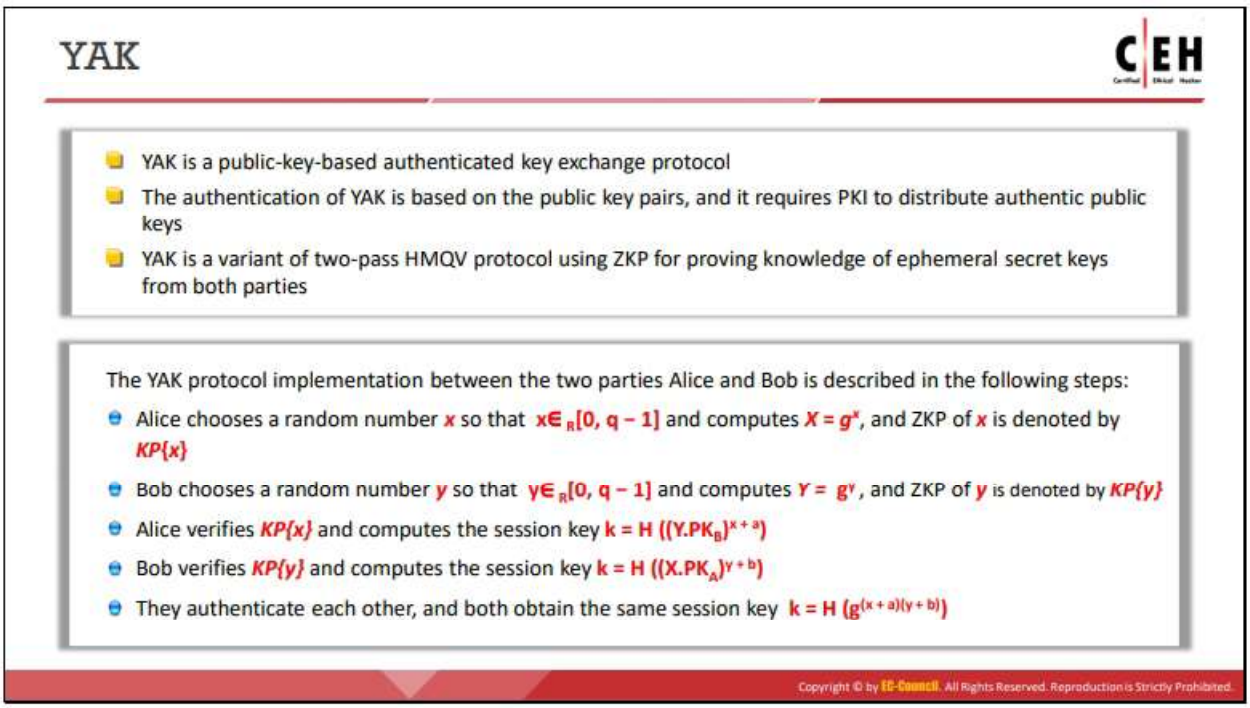
The system has two parameters called *p* and *g*

- Parameter *p* is a prime number
- Parameter *g* (usually called a generator) is an integer less than *p*, with the following property: for every number *n* between 1 and *p-1* (both inclusive), there is a power k of g such that $n = g^k \bmod p$

Many cryptography textbooks use the fictitious characters "Alice" and "Bob" to illustrate cryptography; we will do the same here as well:

- Alice generates a random private value **a**, and Bob generates a random private value **b**. Both a and b are drawn from the **set of integers**
- They derive their public values using parameters p and g and their private values. Alice's public value is $g^a \bmod p$, and Bob's public value is $g^b \bmod p$.
- They exchange their public values
- Alice computes $g^{ab} = (g^b)^a \bmod p$, and Bob computes $g^{ba} = (g^a)^b \bmod p$
- Since $g^{ab} = g^{ba} = k$, Alice and Bob now have a shared secret key **k**

The Diffie–Hellman algorithm does not provide any authentication for the key exchange and is vulnerable to many cryptographic attacks. Nevertheless, it is the basis of many authentication mechanisms; for example, it provides forward secrecy in the TLS protocol's ephemeral modes depending on the cipher spec.



YAK

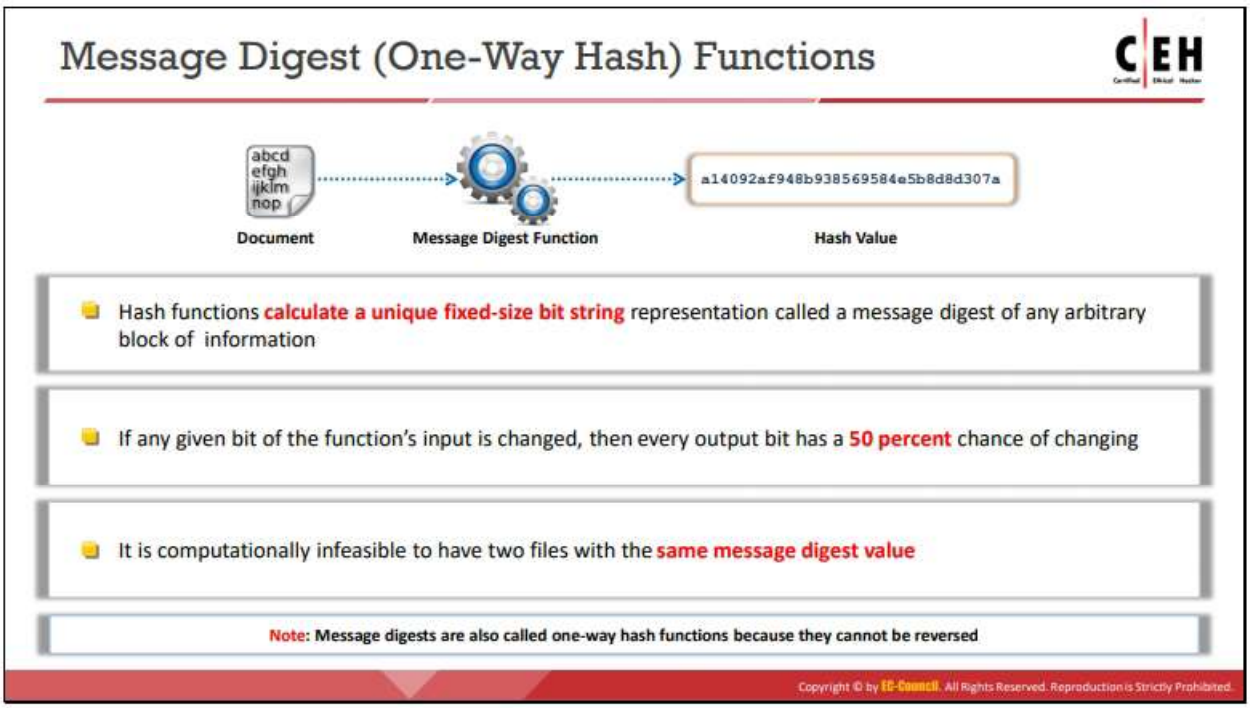
YAK is a public-key-based Authenticated Key Exchange (AKE) protocol. The authentication of YAK is based on public key pairs, and it needs PKI to distribute authentic public keys. YAK is a variant of the two-pass Hashed Menezes-Qu-Vanstone (HMQV) protocol using zero-knowledge proofs (ZKP) for proving the knowledge of ephemeral secret keys from both parties. The YAK protocol lacks joint key control and perfect forward secrecy attributes.

The YAK protocol implementation between two parties Alice and Bob is described as follows:

1. Alice chooses a random number **x** such that $x \in_R [0, q-1]$, computes $X = g^x$, and generates ZKP of **x**, denoted by **KP{x}**. Alice sends **X** and **KP{x}** to Bob.
2. Bob chooses a random number **y** such that $y \in_R [0, q-1]$, computes $Y = g^y$, and generates ZKP of **y**, denoted by **KP{y}**. Bob sends **Y** and **KP{y}** to Alice.
3. Alice verifies the received **KP{x}** and computes the session key after verification as $k = H((Y.PK_B)^{x+a})$, where **H** is a hash function.
4. Bob verifies the received **KP{y}** and computes the session key after verification as $k = H((X.PK_A)^{y+b})$.
5. They authenticate each other, and both obtain the same session key $k = H(g^{(x+a)(y+b)})$.

The YAK protocol can accomplish the following objectives:

- Private key security
- Full forward secrecy
- Session key security



Message Digest (One-way Hash) Functions

Hash functions calculate a unique fixed-size bit string representation, called a message digest, of any arbitrary block of information. Message digest functions distill the information contained in a file (small or large) into a single fixed-length number, typically between 128 and 256 bits. If any given bit of the function's input is changed, every output bit has a 50% chance of changing. Given an input file and its corresponding message digest, it should be nearly impossible to find another file with the same message digest value, as it is computationally infeasible to have two files with the same message digest value.

Message digest functions are also called one-way hash functions because they produce values that are nearly impossible to invert, resistant to attack, mostly unique, and widely distributed. Message digest algorithms themselves do not participate in encryption and decryption operations. They allow the creation of digital signatures and message authentication codes (MACs) as well as the derivation of encryption keys from passphrases.

The main role of a cryptographic hash function is to provide integrity in document management. Cryptographic hash functions are an integral part of digital signatures. They are relatively faster than digital signature algorithms; hence, their characteristic feature is to calculate the signature of the document's hash value, which is smaller than the document. In addition, digests help to hide the contents or source of the document.

Widely used message digest functions include the following algorithms:

- MD5
- SHA

Note: Message digests are also called one-way hash functions because they cannot be reversed.

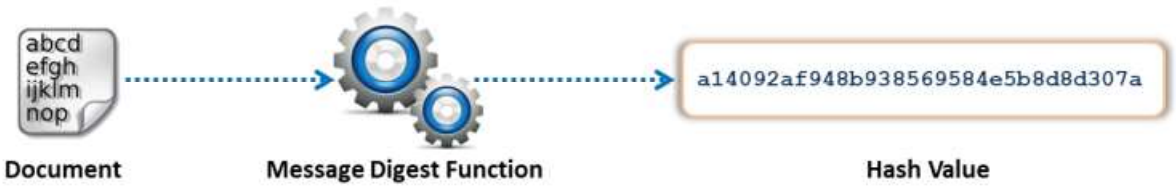
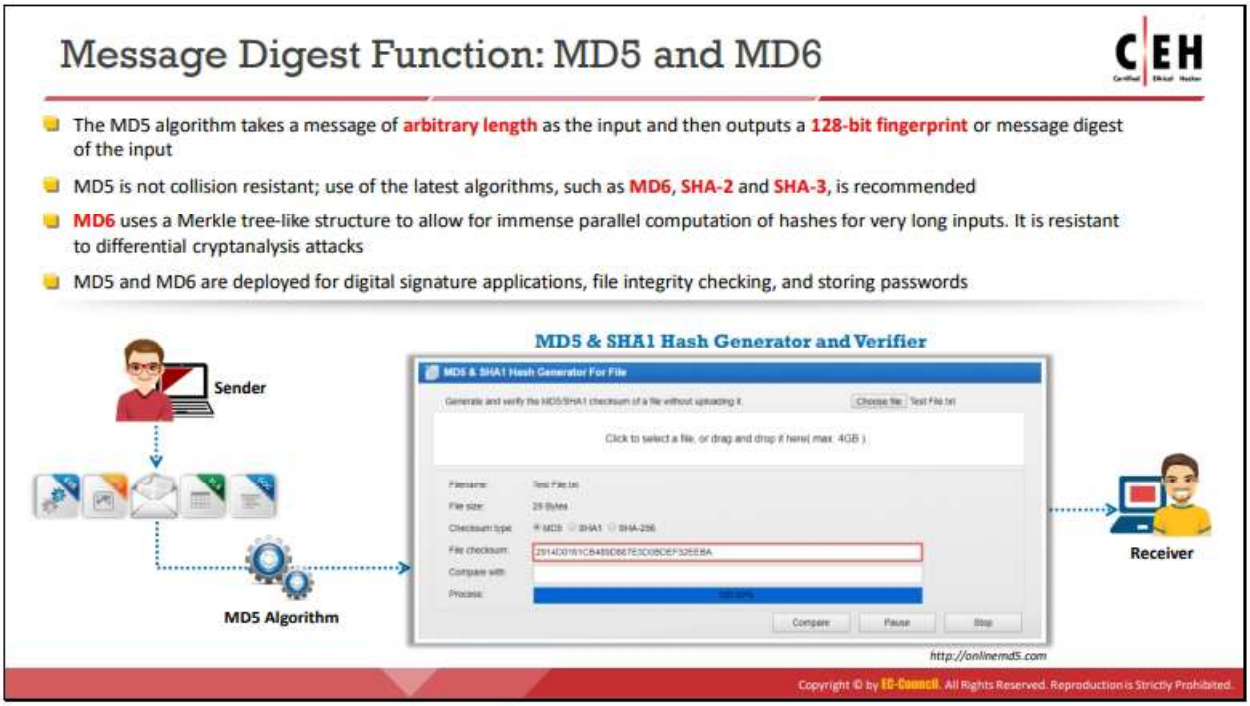


Figure 20.8: Block Diagram of One-way Hash Function



Message Digest Function: MD5 and MD6

MD2, MD4, MD5, and MD6 are **message digest algorithms** used in digital signature applications to compress a document securely before the system signs it with a private key. The algorithms can be of variable length, but the resulting message digest always has a size of 128 bits.

The structures of all three algorithms (MD2, MD4, and MD5) appear similar, although the design of MD2 is reasonably different from that of MD4 and MD5. MD2 supports 8-bit machines, while MD4 and MD5 support 32-bit machines. The algorithm pads the message with extra bits to ensure that the number of bits is divisible by 512. The extra bits may include a 64-bit binary message.

Attacks on versions of MD4 have become increasingly successful. Research has shown how an attacker launches collision attacks on the full version of MD4 within a minute on a typical PC. MD5 is slightly more secure but is slower than MD4. However, both the message digest size and the padding requirements remain the same.

MD5 is a widely used cryptographic hash function that takes a message of arbitrary length as input and outputs a 128-bit (16-byte) fingerprint or message digest of the input. MD5 can be used in a wide variety of cryptographic applications and is useful for digital signature applications, file integrity checking, and storing passwords. However, MD5 is not collision resistant; therefore, it is better to use the latest algorithms, such as MD6, SHA-2, and SHA-3.

MD6 uses a Merkle-tree-like structure to allow for large-scale parallel computation of hashes for very long inputs. It is resistant to differential cryptanalysis attacks.

To calculate the effectiveness of hash functions, check the output produced when the algorithm randomizes an arbitrary input message.

The following are examples of minimally different message digests:

- echo "There is CHF1500 in the blue bo" | md5sum
  e41a323bdf20eadafd3f0e4f72055d36
- echo "There is CHF1500 in the blue box" | md5sum
  7a0da864a41fd0200ae0ae97afd3279d
- echo "There is CHF1500 in the blue box." | md5sum
  2db1ff7a70245309e9f2165c6c34999d

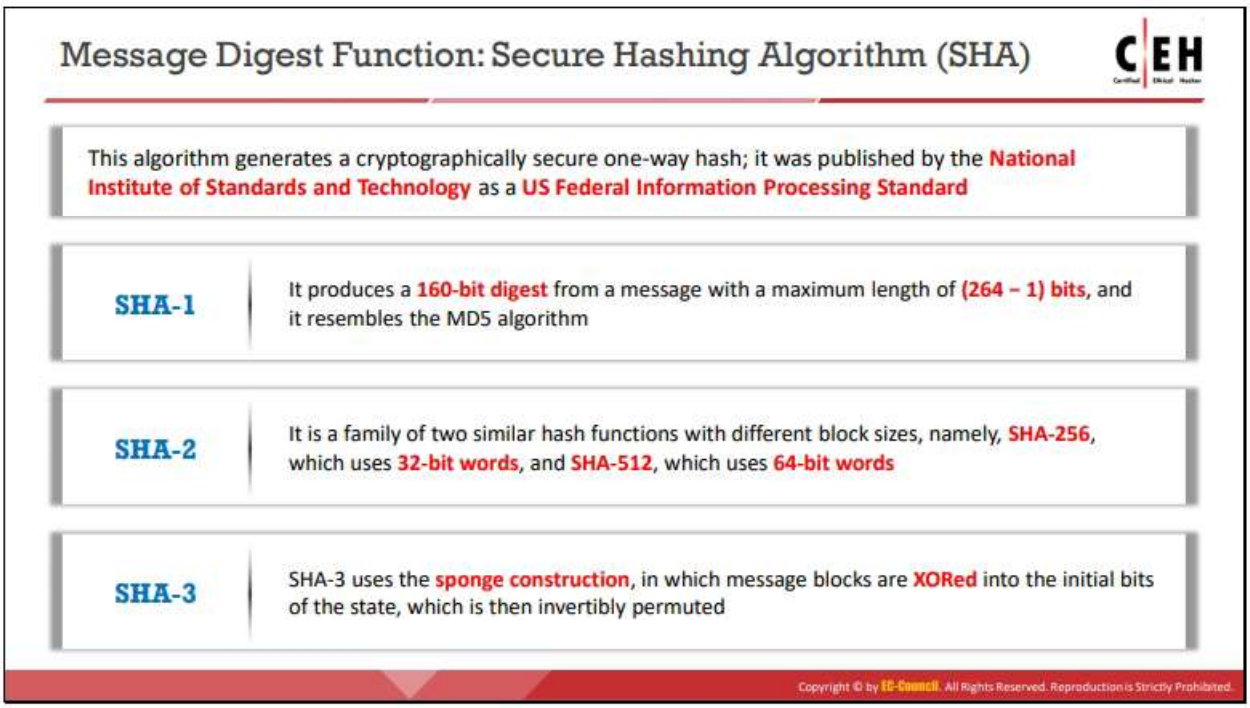
Even minimally different texts produce radically different MD5 codes.

Figure 20.9: Verifying MD5 Hash

- **Onlinemd5**

  Source: *http://onlinemd5.com*

  Onlinemd5 generates and checks file integrity using secure time-proven algorithms such as MD5, SHA-1, and SHA-256. One can create checksums (digital fingerprints) of files and verify their integrity using this online tool.



Message Digest Function: Secure Hashing Algorithm (SHA)

The NIST has developed the Secure Hash Algorithm (SHA), specified in the **Secure Hash Standard** (**SHS**) and published as a federal information-processing standard (FIPS PUB 180). It generates a cryptographically secure one-way hash. Rivest developed the SHA, which is similar to the message digest algorithm family of hash functions. It is slightly slower than MD5, but its larger message digest makes it more secure against brute-force collision and inversion attacks.

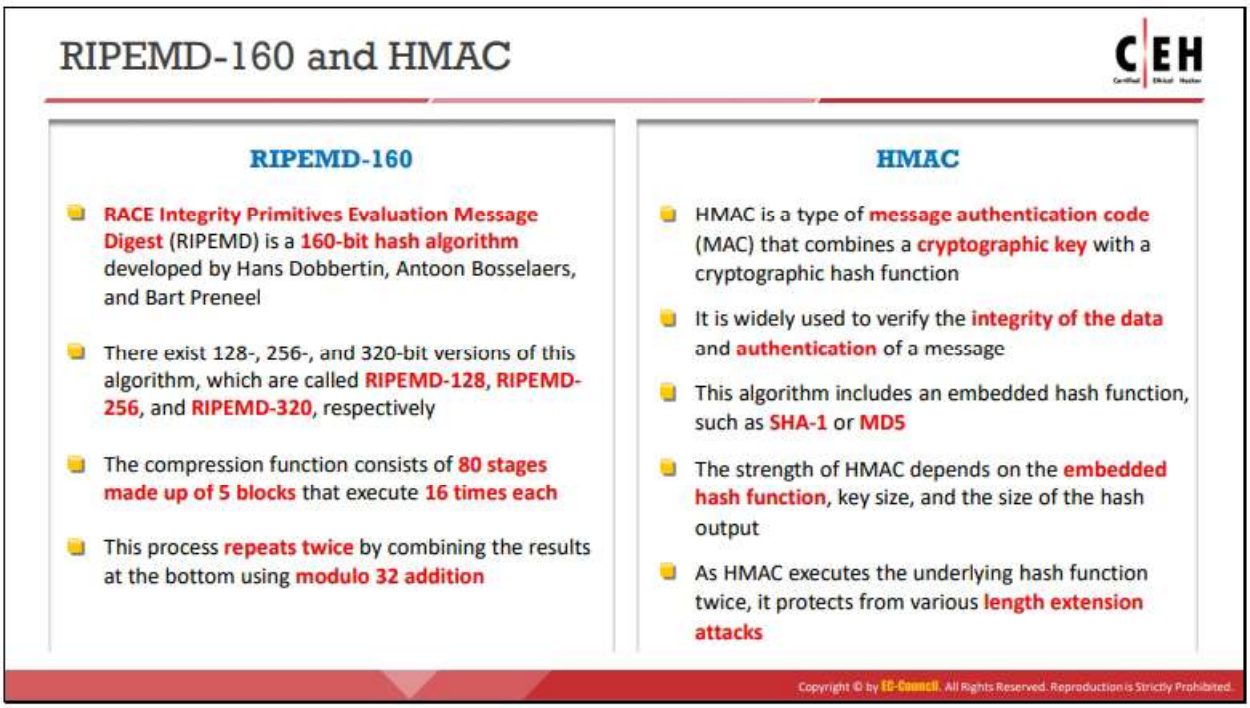
SHA encryption is a series of five different cryptographic functions, and it currently has three generations: SHA-1, SHA-2, and SHA-3.

- **SHA-0**: A retronym applied to the original version of the 160-bit hash function published in 1993 under the name SHA, which was withdrawn from trade due to an undisclosed "**significant flaw**" in it. It was replaced with a slightly revised version, namely SHA-1.
- **SHA-1**: It is a 160-bit hash function that resembles the former MD5 algorithm developed by Ron Rivest. It produces a 160-bit digest from a message with a maximum length of (264 − 1) bits. It was designed by the National Security Agency (NSA) to be part of the Digital Signature Algorithm (DSA). It is most commonly used in security protocols such as PGP, TLS, SSH, and SSL. As of 2010, SHA-1 is no longer approved for cryptographic use because of its cryptographic weaknesses.
- **SHA-2**: SHA2 is a family of two similar hash functions with different block sizes, namely SHA-256, which uses 32-bit words, and SHA-512, which uses 64-bit words. The truncated versions of each standard are SHA-224 and SHA-384.
- **SHA-3**: SHA-3 uses sponge construction in which message blocks are XORed into the initial bits of the state, which the algorithm then invertibly permutes. It supports the same hash lengths as SHA-2 but differs in its internal structure considerably from the rest of the SHA family.

Comparison of SHA functions (SHA-0, SHA-1, SHA-2, and SHA-3).

Algorithm and variant		Output size (bits)	Internal state size (bits)	Block Size (bits)	Maximum message size (bits)	Rounds	Operations	Security (bits)
MD5 (as reference)		128	128 (4*32)	512	2^{64}-1	64	Add mod 2^{32}, and, or, xor, rot	<=18 (collisions found)
SHA-0		160	160 (5*32)	512	2^{64}-1	80	Add mod 2^{32}, and, or, xor, rot	<34 (collisions found)
SHA-1		160	160 (5*32)	512	2^{64}-1	80	Add mod 2^{32}, and, or, xor, rot	<63 (collisions found)
SHA-2	SHA-224 SHA-256	224 256	256 (8*32)	512	2^{64}-1	64	Add mod 2^{32}, and, or, xor, shr, rot	112 128
	SHA-384 SHA-512 SHA-512/224 SHA-512/256	384 512 224 256	512 (8*64)	1024	2^{128}-1	80	Add mod 2^{64}, and, or, xor, shr, rot.	192 256 112 128
SHA-3	SHA3-224 SHA3-256 SHA3-384 SHA3-512 SHAKE128 sHAKE256	224 256 384 512 d(arbitrary) d(arbitrary)	1600 (5*5*64)	1152 1088 832 576 1344 1088	∞	24	And, xor, not, rot	112 128 192 256 Min(d/2,128) Min(d/2,256)

Table 20.2: Comparison between SHA-0, SHA-1 and SHA-2 functions



RIPEMD-160

RACE Integrity Primitives Evaluation Message Digest (RIPEMD) is a 160-bit hash algorithm developed by Hans Dobbertin, Antoon Bosselaers, and Bart Preneel. There exist 128-, 256-, and 320-bit versions of this algorithm, called RIPEMD-128, RIPEMD-256, and RIPEMD-320, respectively. These algorithms replace the original RIPEMD, which was found to have a collision issue. They do not follow any standard security policies or guidelines.

RIPEMD-160 is a more secure version of the RIPEMED algorithm. In this algorithm, the compression function consists of 80 stages, i.e., 5 blocks that execute 16 times each. This process repeats twice by combining the results at the bottom using modulo 32 addition.

HMAC

Hash-based message authentication code (HMAC) is a type of message authentication code (MAC) that uses a cryptographic key along with a cryptographic hash function. It is widely used to verify the integrity of data and authentication of a message. This algorithm includes an embedded hash function such as SHA-1 or MD5. The strength of HMAC depends on the embedded hash function, key size, and size of the hash output.

HMAC includes two stages for computing the hash. The input key is processed to produce two keys, namely the inner key and the outer key. The first stage of the algorithm inputs the inner key and message to produce an internal hash. The second stage of the algorithm inputs the output from the first stage and outer key, and produces the final HMAC code.

As HMAC executes the underlying hash function twice, it offers protection against various length extension attacks. The size of the key and the output depends on the embedded hash function; e.g., 128 or 160 bits in the case of MD5 or SHA-1, respectively.

CHAP

The Challenge-Handshake Authentication Protocol (CHAP) is an authentication mechanism used by Point-to-Point Protocol (PPP) servers to authenticate or validate the identity of remote clients or network hosts. It is more secure and effective compared to Password Authentication Procedure (PAP), as it regularly verifies the identity of the client using a three-way handshake and provides protection against replay attacks.

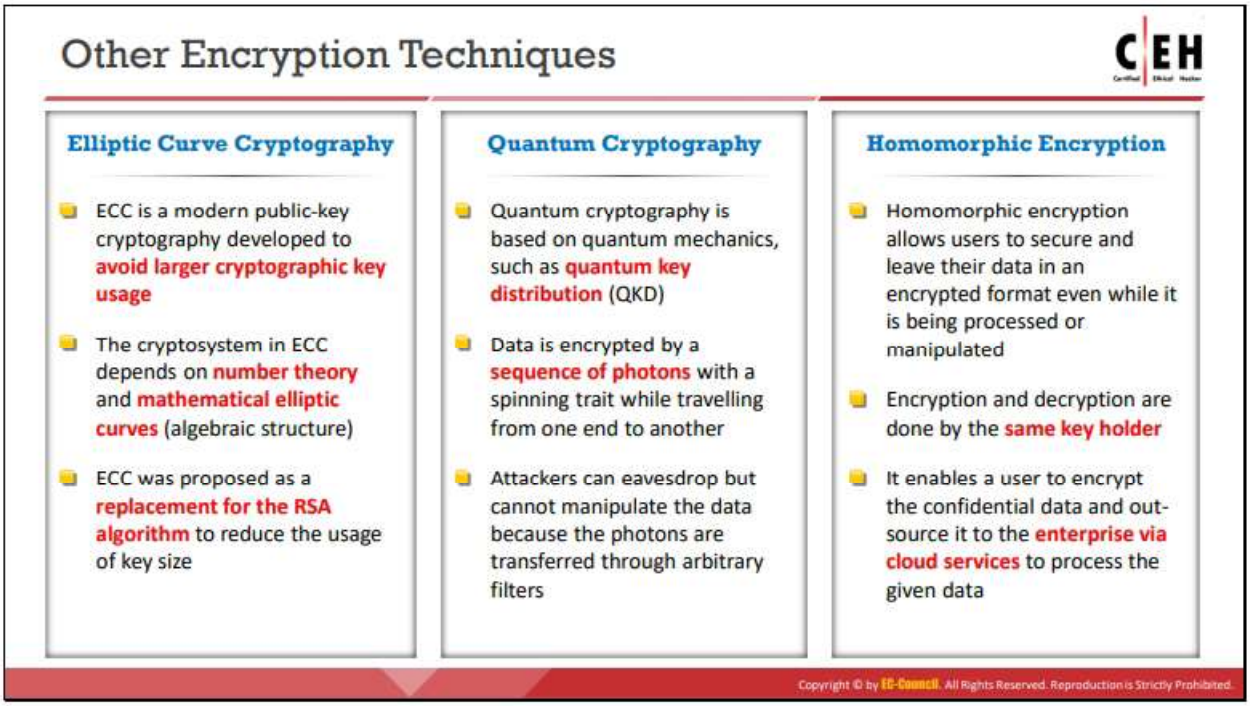
EAP

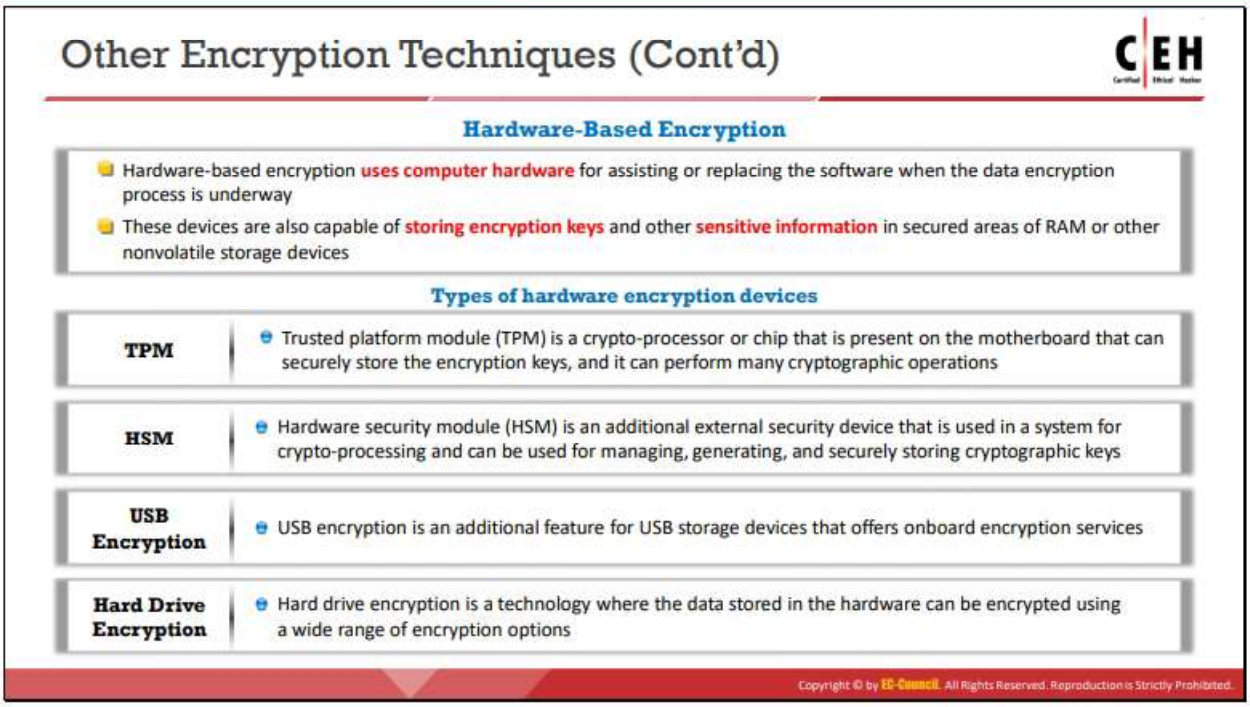
The Extensible Authentication Protocol (EAP) is an authentication protocol that was originally designed for point-to-point connections. It is used as an alternative to the CHAP and PAP authentication protocols, as it is more secure and supports different authentication mechanisms such as passwords, smart tokens, one-time passwords (OTPs), secure ID card, digital certificates, and public-key encryption mechanisms. After the selection of the EAP authentication mechanism, a session is established and messages are exchanged between the client and the authenticating server. The session consists of requests and responses for authentication information. The length and details of the authentication session are determined by the EAP authentication mechanism used.

GOST – Hash Function

This hash algorithm was initially defined in the Russian national standard GOST R 34.11-94 "Information Technology - Cryptographic Information Security - Hash Function."

It produces a fixed-length output of 256 bits. The input message is broken up into chunks of 256-bit blocks. If a block is less than 256 bits, then the message is padded by appending as many zeros to it as are required to make the length of the message 256 bits. The remaining bits are filled with a 256-bit integer arithmetic sum of all previously hashed blocks. Then, a 256-bit integer representing the length of the original message, in bits, is produced.





Other Encryption Techniques

- **Elliptic Curve Cryptography (ECC)**

  ECC is a modern public-key cryptography developed to avoid larger cryptographic key usage. The asymmetric cryptosystem depends on number theory and mathematical elliptic curves (algebraic structure) to generate short, quick, and robust cryptographic keys. RSA is an incumbent public-key algorithm, but its key size is large. The speed of the

encryption always depends on the key size: a smaller key length allows faster encryption. To minimize the key size, elliptic curve cryptography has been proposed as a replacement for the RSA algorithm.

The operational key sizes of both algorithms to achieve similar goals are listed below:

ECC Key size	RSA Key Size
160	1024
224	2048
256	3072
384	7680
512	15360

Table 20.3: Comparison of ECC and RSA key size

While RSA uses a key size of 1024 to encrypt the data, ECC provides equal security with a comparatively smaller key size of 160. For high-level computing, RSA uses a key size of 7680 to implement security, whereas ECC can provide the same level of security with a key size of 384.

- **Quantum Cryptography**

  As the world is increasingly adopting online information sharing, cryptosystems are witnessing a sharp increase in security attacks. Since mathematical encryption uses binary digits (0 and 1), it can be easily eavesdropped on or manipulated using various techniques. Hence, quantum cryptography has been introduced to protect data from theft midway (e.g., MITM attacks). This cryptography is processed based on quantum mechanics, such as quantum key distribution (QKD), using photons instead of mathematics as a part of encryption.

  In quantum cryptography, the data are encrypted by a sequence of photons that have a spinning trait while traveling from one end to another end. These photons keep changing their shapes during their course through filters: vertical, horizontal, forward slash, and backslash. Here, vertical and backslash spins imply "ones," while horizontal and forward slash spins imply "zeros."

  - Horizontal (–): 0
  - Vertical (|): 1
  - Backslash (/): 1
  - Forward slash (\): 0

  Attackers can eavesdrop on but cannot manipulate the data because the photons are transferred through arbitrary filters. To breach this mechanism, attackers have to know the exact shape of the photons; if they fail to choose the right transmission, the photon polarization is distorted and the receiver detects an error indicating the eavesdrop.

- **Homomorphic Encryption**

  Homomorphic encryption differs from conventional encryption mechanisms, where math operations are performed to encrypt the plaintext. Homographic encryption allows users to secure and leave their data in an encrypted format even while it is being processed or manipulated. In this technique, encryption and decryption are performed by the same key holder. The homomorphic mechanism enables the user/sender to encrypt the confidential data and out-source it to an enterprise via cloud services to process the given data.

  How homomorphic encryption differs from other encryption mechanisms:

  In private key encryption:

  - Only keyholders can generate and decrypt ciphertexts using similar keys.

  In public key encryption:

  - Only the public keyholder generates the ciphertext and the secret keyholder decrypts the ciphertext.

  In homomorphic encryption:

  - The keyholder can generate the ciphertext and anyone can alter the ciphertext, but only the keyholder again can decrypt the data.

  The reason for using this cryptography is that an untrusted entity can manipulate the data. Hence, this mechanism allows the sender himself/herself to encrypt and decrypt the data, allowing anyone to perform mathematical operations on the ciphertext with respect to the rules applied by the sender.

- **Hardware-Based Encryption**

  Hardware-based encryption is a technique that uses computer hardware for assisting or replacing the software when the data encryption process is being performed. Devices that offer encryption techniques can be considered as hardware-based encryption devices. In the implementation of hardware-based encryption, the cryptography technique workload is transferred to the hardware processors, making the system resources free for performing other functions. These devices can also store encryption keys and other sensitive information in secured areas of RAM or other nonvolatile storage devices such as flash memory.

  Hardware encryption devices reduce instruction sets, where only the authorized code can be executed. These devices do not support third-party software, thereby preventing the execution of any malicious programs. Hardware encryption offers many advantages over software encryption, as it can perform rapid processing of algorithm. It provides tamper-resistant key storage and avoids unauthorized code. Some hardware-based encryption devices are wireless access points, Nitrokey, credit card terminals, and network bulk encryptors.

Types of hardware encryption devices

- **TPM**

  Trusted Platform Module (TPM) is a crypto-processor or a chip that is present in the motherboard. It can securely store the encryption keys and perform many cryptographic operations. TPM offers various features such as authenticating platform integrity, providing full disk encryption capabilities, performing password storage, and providing software license protection.

- **HSM**

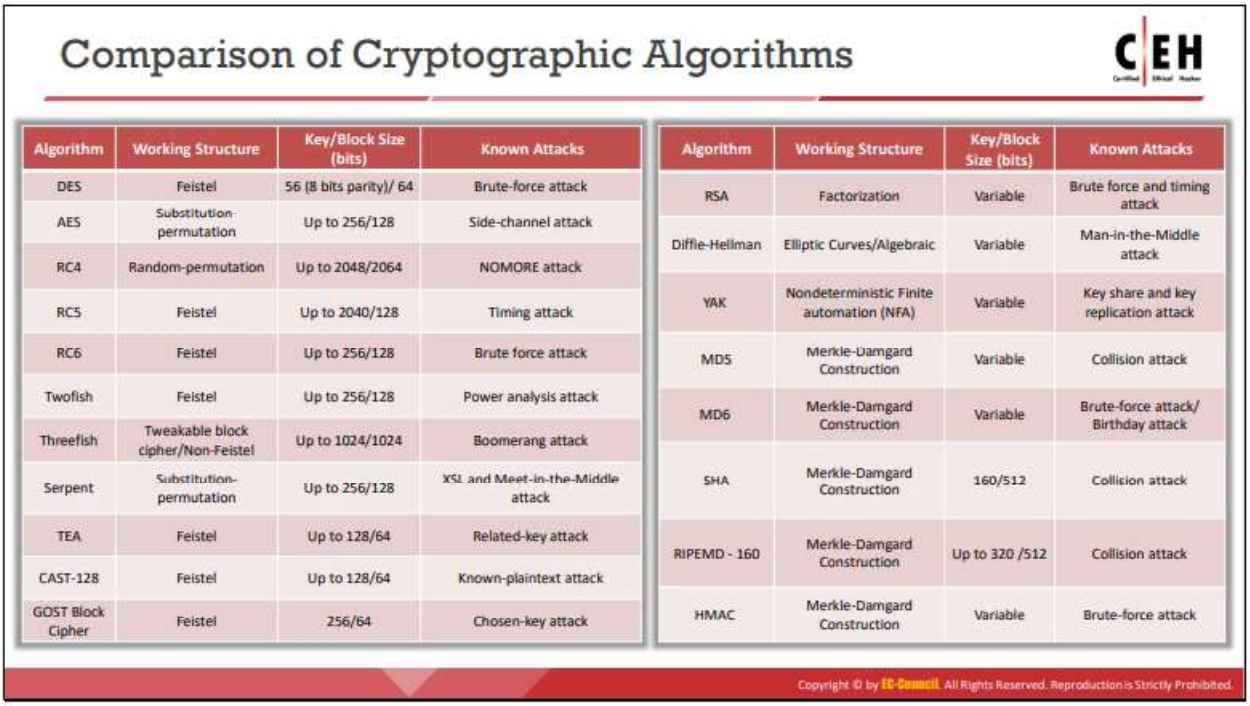
  A hardware security module (HSM) is an additional external security device that is used in a system for crypto-processing, and it can be used for managing, generating, and securely storing cryptographic keys. HSM offers enhanced encryption computation that is useful for symmetric keys longer than 256 bits. High-performance HSM devices are connected to the network using TCP/IP. Some HSM devices include SafeNet Luna Network HSM, nSheild, Cloud HSM, and Cryptosec Dekaton.

- **USB Encryption**

  USB encryption is an additional feature for USB storage devices, which offers onboard encryption services. Encrypted USB devices need an on-device credential system or software- or hardware-based credentials from a computer. USB encryption provides protection against malware distribution over USB and helps in preventing data loss and data leakage. Some hardware USB-encrypted devices include Crypto USB, Kingston Ironkey D300S, and diskAshur Pro 500GB.

- **Hard Drive Encryption**

  Hard drive encryption is a technology whereby the data stored in the hardware can be encrypted using a wide range of encryption options. Hard drive encryption devices cannot use an on-device keyboard or fingerprint reader; instead, they need a TPM or an HSM. These devices can be installed as an internal drive on a computer. Some hard drive encryption devices include military-grade 256-bit AES Hardware Encryption and DiskCypher AES Sata Hard Drive Encryption.



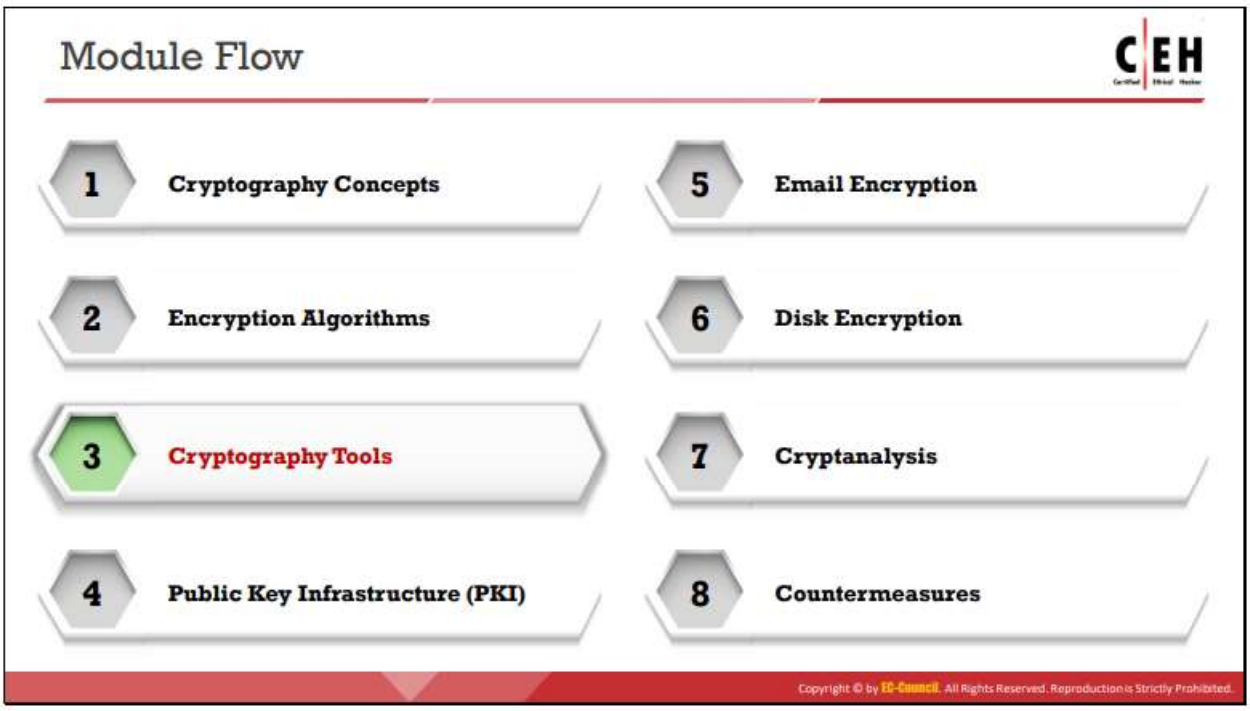
Comparison of Cryptographic Algorithms

The following table compares the various cryptographic algorithms and lists the known attacks against these algorithms:

Algorithm	Working Structure	Key/Block Size (bits)	Known Attacks
DES	Feistel	56 (8 bits parity)/64	Brute-force attack
AES	Substitution-permutation	Up to 256/128	Side-channel attack
RC4	Random-permutation	Up to 2048/2064	NOMORE attack
RC5	Feistel	Up to 2040/128	Timing attack
RC6	Feistel	Up to 256/128	Brute-force attack
Twofish	Feistel	Up to 256/128	Power analysis attack
Threefish	Tweakable block cipher/Non-Feistel	Up to 1024/1024	Boomerang attack
Serpent	Substitution-permutation	Up to 256/128	XSL and Meet-in-the-Middle attack
TEA	Feistel	Up to 128/64	Related-key attack
CAST-128	Feistel	Up to 128/64	Known-plaintext attack

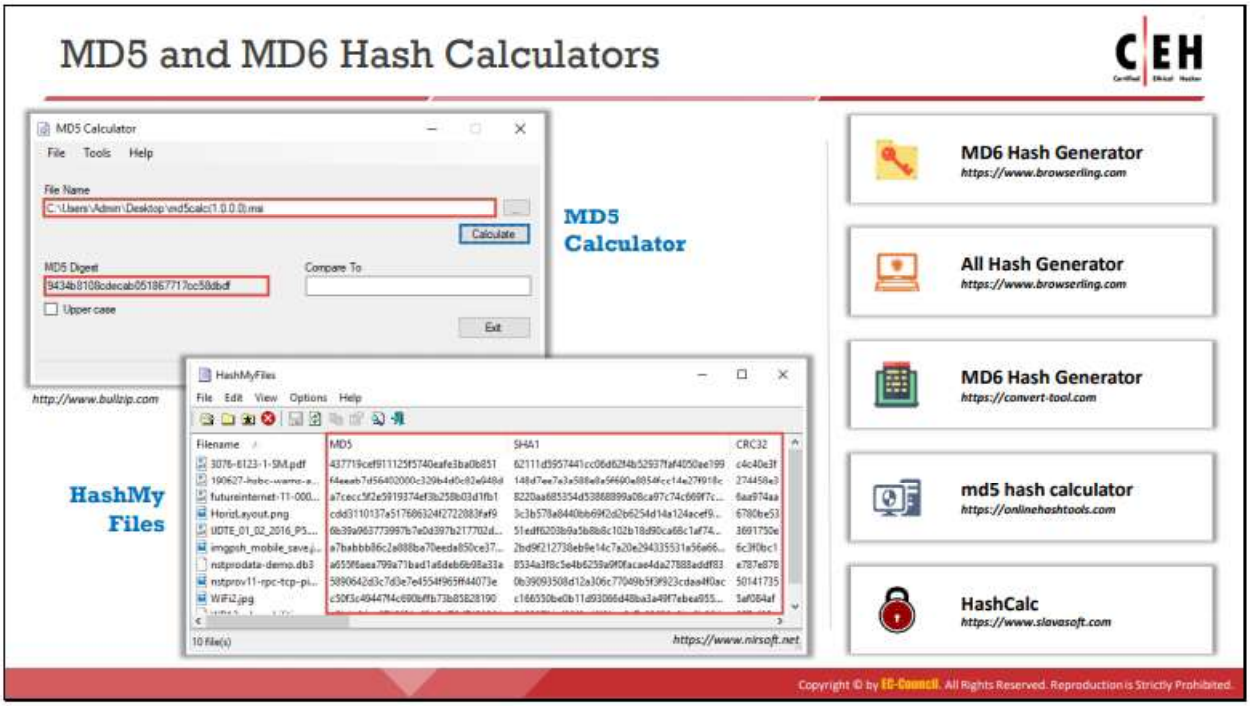
GOST Block Cipher	Feistel	256/64	Chosen-key attack
RSA	Factorization	Variable	Brute-force and timing attack
Diffie–Hellman	Elliptic curves/Algebraic	Variable	Man-in-the-Middle attack
YAK	Nondeterministic finite automation (NFA)	Variable	Key share and key replication attack
MD5	Merkle–Damgard Construction	Variable	Collision attack
MD6	Merkle–Damgard Construction	Variable	Brute-force attack/Birthday attack
SHA	Merkle–Damgard Construction	Variable	Collision attack
RIPEMD - 160	Merkle–Damgard Construction	Up to 320/512	Collision attack
HMAC	Merkle–Damgard Construction	Variable	Brute-force attack

Table 20.4: Comparison of cryptographic algorithms



Cryptography Tools

This section deals with various cryptography tools that you can use to encrypt sensitive data to protect it from unauthorized access by any party other than the person for whom it is intended.



MD5 and MD6 Hash Calculators

MD5 and MD6 hash calculators that use different hash algorithms to convert plaintext into its equivalent hash value are discussed below.

- **MD5 Calculator**

  Source: *http://www.bullzip.com*

  MD5 Calculator is a simple application that calculates the MD5 hash of a given file. It can be used with large files (e.g., several gigabytes in size). It features a progress counter and a text field from which the final MD5 hash can be easily copied to the clipboard. MD5 Calculator can be used to check the integrity of a file.

  It allows you to calculate the MD5 hash value of the selected file. Right-click the file and choose "**MD5 Calculator**;" the program will calculate the MD5 hash. The MD5 Digest field contains the calculated value. To compare this MD5 digest with another, one can paste the other value into the Compare To field. Obviously, an equal to sign ("=") appears between the two values if they are equal; otherwise, the less than ("<") or greater than (">") sign will tell you that the values are different.

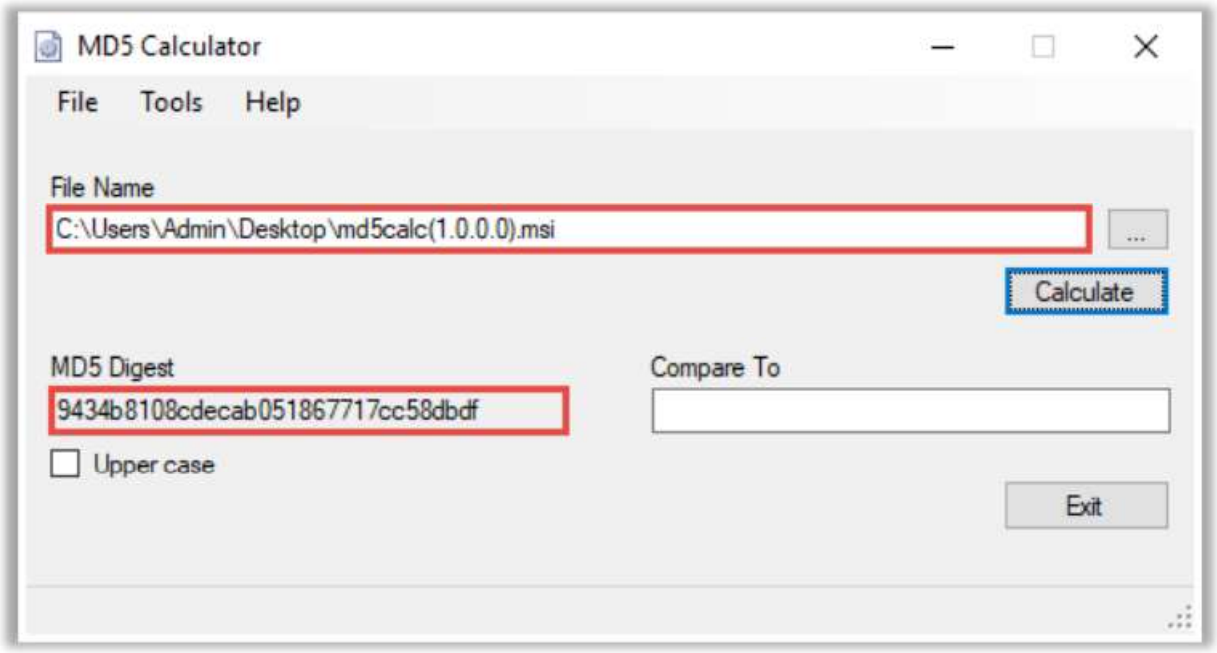


Figure 20.10: Screenshot of MD5 Calculator

- **HashMyFiles**

  Source: *https://www.nirsoft.net*

  HashMyFiles is a utility that allows you to calculate the MD5 and SHA1 hashes of one or more files in the system. It allows you to copy the MD5/SHA1 hash list to the clipboard or save it in a text/html/xml file. You can launch HashMyFiles from the context menu of Windows Explorer and display the MD5/SHA1 hashes of the selected files or folders.

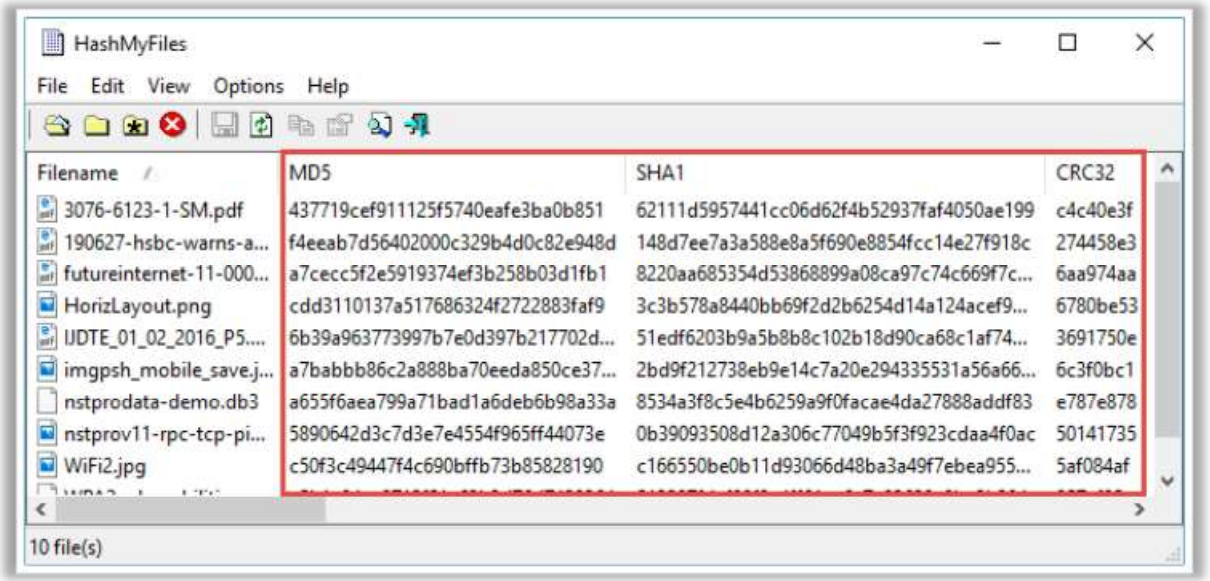
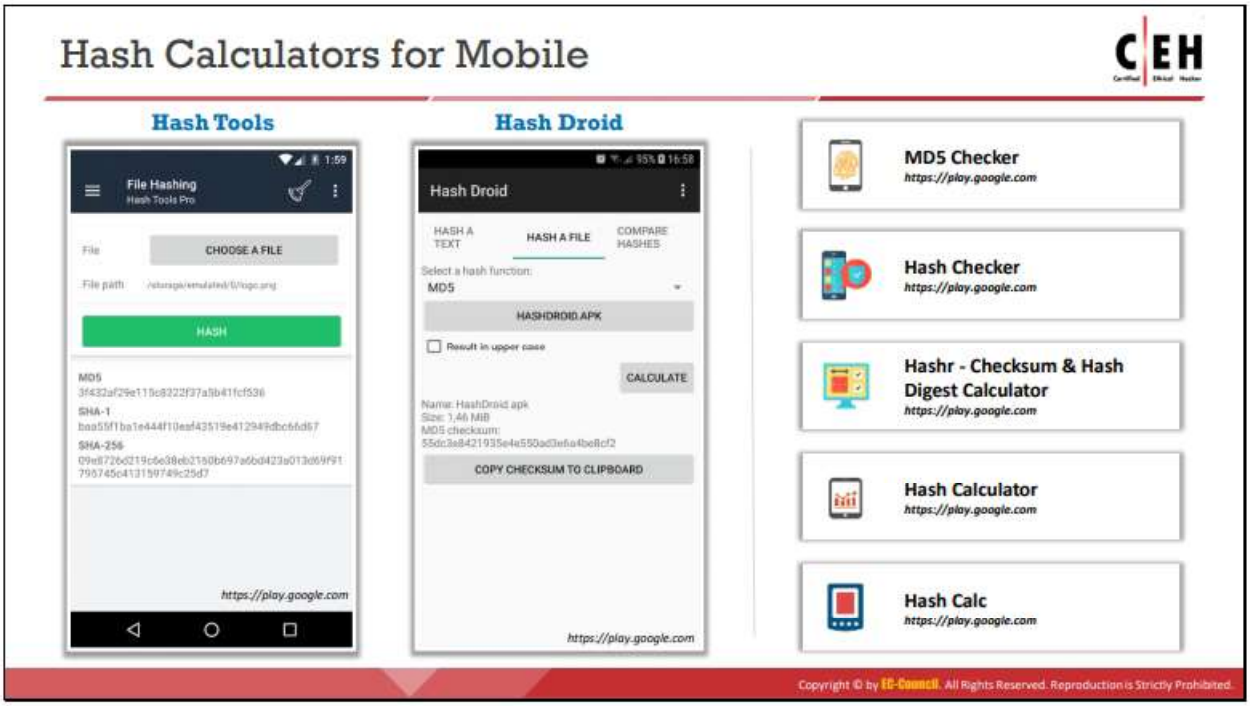


Figure 20.11: Screenshot of HashMyFiles

Some additional MD5 and MD6 hash calculators are as follows:

- MD6 Hash Generator (*https://www.browserling.com*)
- All Hash Generator (*https://www.browserling.com*)
- MD6 Hash Generator (*https://convert-tool.com*)
- md5 hash calculator (*https://onlinehashtools.com*)
- HashCalc (*https://www.slavasoft.com*)



Hash Calculators for Mobile

Some hash calculators for mobile devices are discussed below.

- **Hash Tools**

  Source: *https://play.google.com*

  Hash Tools is a utility for calculating a hash from a given text or decrypting a hash to its original text. In this application, the available hash functions are MD4, MD5, SHA-1, SHA-256, SHA-384, SHA-512, and NTLM.

Figure 20.12: Screenshot of Hash Tools

- **Hash Droid**

  Source: *https://play.google.com*

  The Hash Droid utility helps to calculate a hash from a given text or a file stored on the device. In this application, the available hash functions are Adler-32, CRC-32, Haval-128, MD2, MD4, MD5, RIPEMD-128, RIPEMD-160, SHA-1, SHA-256, SHA-384, SHA-512, Tiger, and Whirlpool.

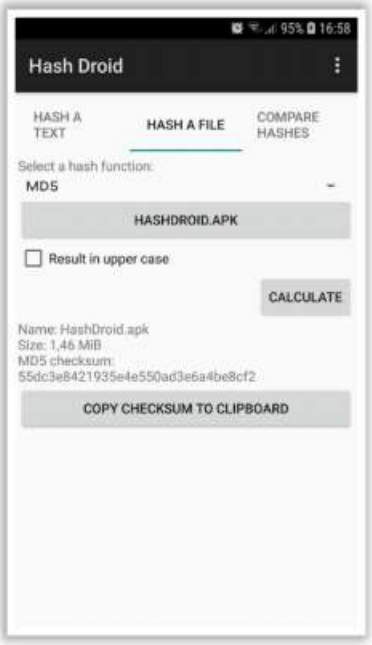
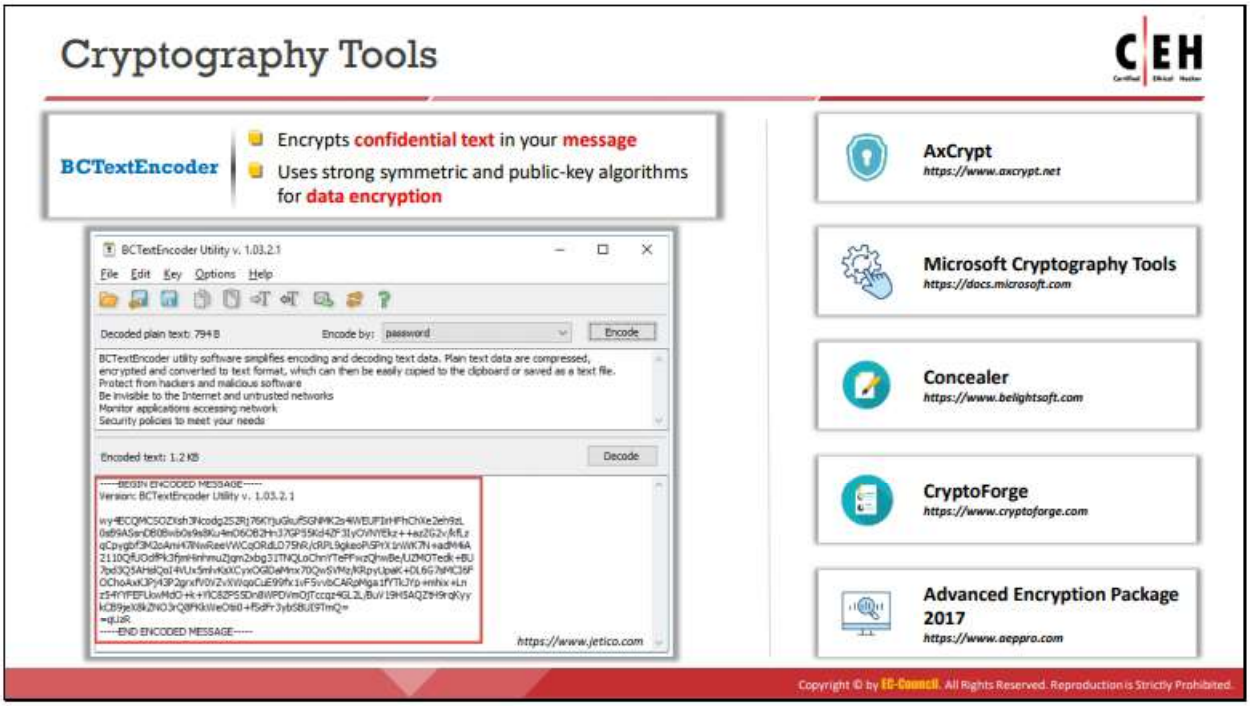


Figure 20.13: Screenshot of Hash Droid

Some additional MD5 hash calculators are as follows:

- MD5 Checker (*https://play.google.com*)
- Hash Checker (*https://play.google.com*)
- Hashr - Checksum & Hash Digest Calculator (*https://play.google.com*)
- Hash Calculator (*https://play.google.com*)
- Hash Calc (*https://play.google.com*)



Cryptography Tools

You can use various cryptographic tools for encrypting and decrypting your information, files, etc. These tools implement different types of encryption algorithms.

- **BCTextEncoder**

  Source: *https://www.jetico.com*

  The BCTextEncoder utility simplifies the encoding and decoding of text data. It compresses, encrypts, and converts plaintext data into text format, which the user can then copy to the clipboard or save as a text file. It uses public key encryption methods as well as password-based encryption. Furthermore, it uses strong and approved symmetric and public-key algorithms for data encryption.

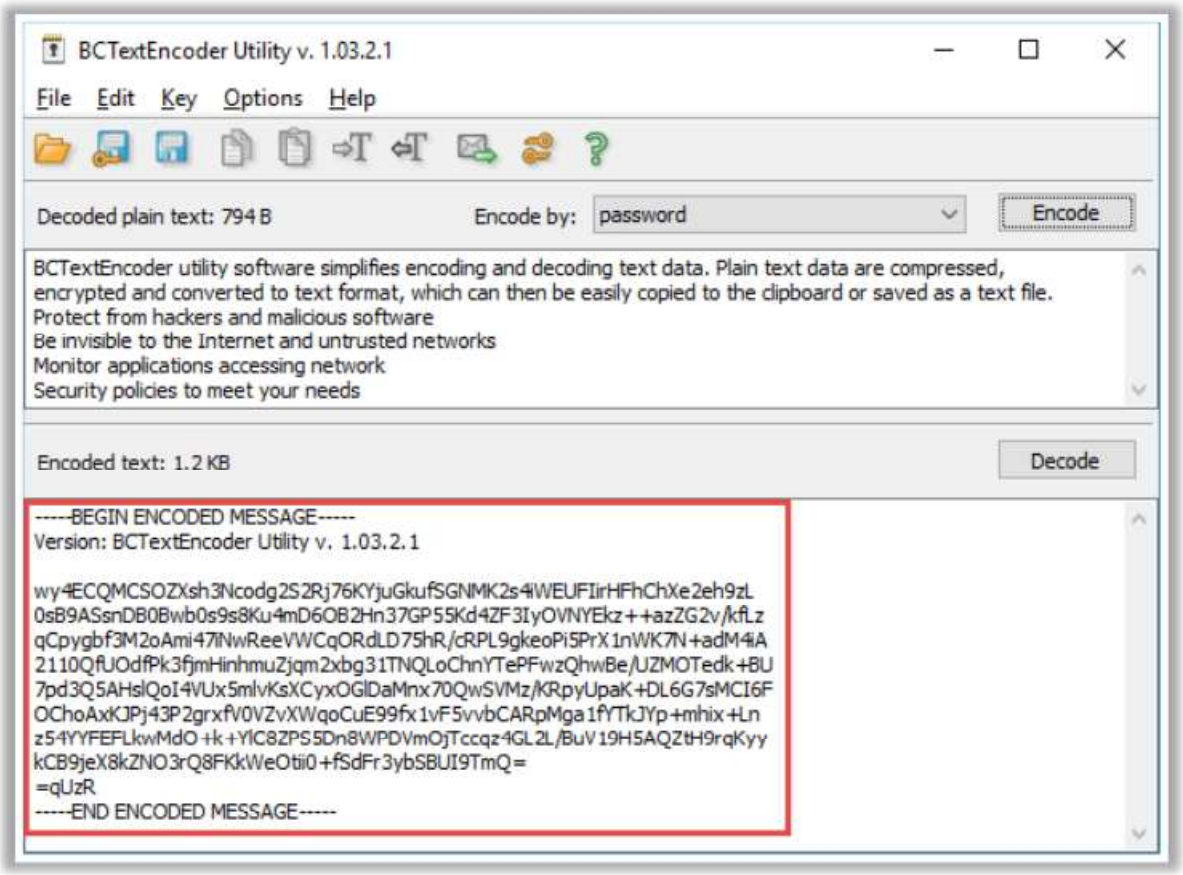


Figure 20.14: Screenshot of BCTextEncoder

Some additional cryptography tools are as follows:

- AxCrypt (*https://www.axcrypt.net*)
- Microsoft Cryptography Tools (*https://docs.microsoft.com*)
- Concealer (*https://www.belightsoft.com*)
- SensiGuard (*https://www.sensiguard.com*)
- Challenger (*https://www.encryption-software.de*)

Cryptography Tools for Mobile

Some cryptographic tools for mobile devices are discussed below:

- **Secret Space Encryptor**

  Source: *https://paranoiaworks.mobi*

  Secret Space Encryptor is an integrated solution for password management, message (text) encryption, and file encryption. It keeps messages, notes, and other text safe from unintended readers. It uses encryption algorithms such as AES (Rijndael) 256bit, RC6 256bit, Serpent 256bit, Blowfish 256bit/448bit, Twofish 256bit, and GOST 256bit.

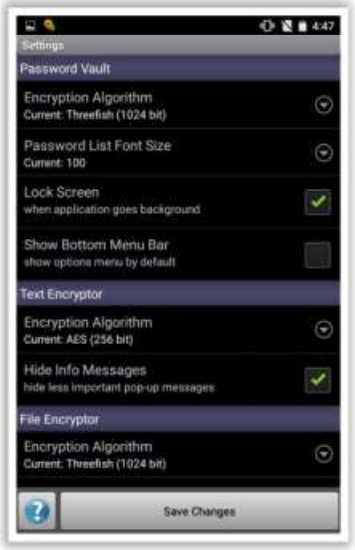


Figure 20.15: Screenshot of Secret Space Encryptor

- **Secure Everything**

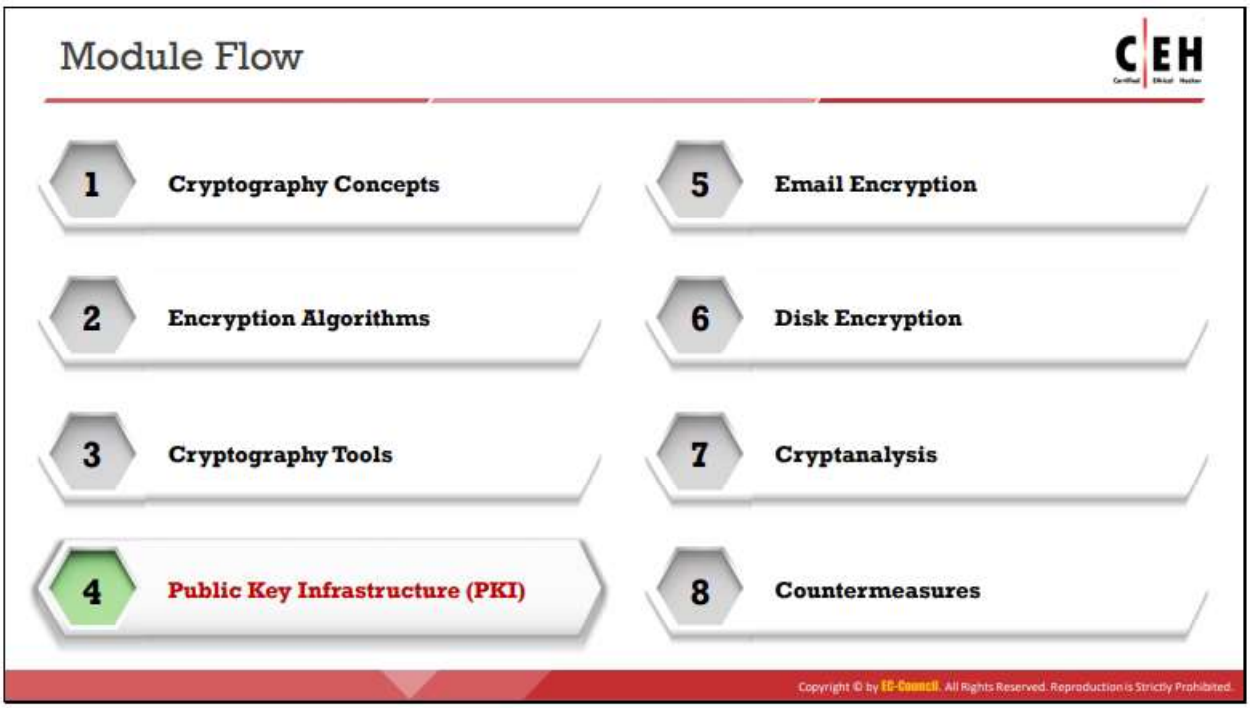
  Source: *https://play.google.com*

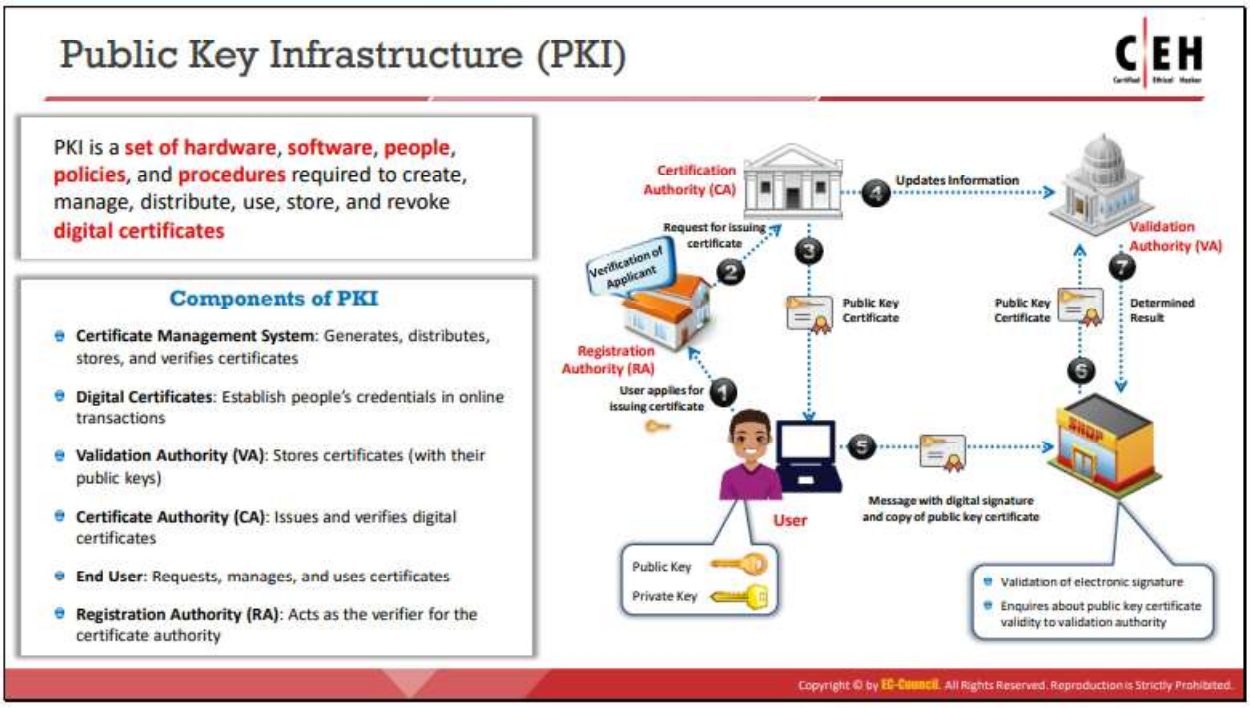
  Secure Everything uses AES encryption to secure SMS, videos, images, audio files, etc. This tool also helps in securing credit card details, bank account details, SSN, etc.

Figure 20.16: Screenshot of Secure Everything

Some additional cryptography tools for mobile devices are as follows:

- Crypto (*https://play.google.com*)
- Encrypt File Free (*https://play.google.com*)
- EgoSecure Encryption Anywhere (*https://play.google.com*)
- Cipher Sender (*https://play.google.com*)
- Decrypto (*https://play.google.com*)





Public Key Infrastructure (PKI)

This section deals with public key infrastructure (PKI) and the role of each component of PKI, certification authorities such as Comodo, IdenTrust, Symantec, and GoDaddy, and signed certificates (CA) vs. the self-signed certificates.

PKI is a security architecture developed to increase the confidentiality of information exchanged over the insecure Internet. It includes hardware, software, people, policies, and procedures

required to create, manage, distribute, use, store, and revoke digital certificates. In cryptography, the PKI helps to bind public keys with corresponding user identities by means of a certification authority (CA).

Components of PKI

- **Certificate Management System**: Generates, distributes, stores, and verifies certificates
- **Digital Certificates**: Establishes credentials of a person when performing online transactions
- **Validation Authority (VA)**: Stores certificates (with their public keys)
- **Certification Authority (CA)**: Issues and verifies digital certificates
- **End User**: Requests, manages, and uses certificates
- **Registration Authority (RA)**: Acts as the verifier for the CA

PKI is a comprehensive system that allows the use of public-key encryption and digital signature services across a wide variety of applications. PKI authentication depends on digital certificates (also known as public-key certificates) that CAs sign and provide. A digital certificate is a digitally signed statement with a public key and the subject (user, company, or system) name in it.

PKI uses public-key cryptography, which is widely used on the Internet to encrypt messages or authenticate message senders. In public-key cryptography, a CA generates public and private keys with the same algorithm simultaneously. The private key is held only by the subject (user, company, or system) mentioned in the certificate, while the public key is made publicly available in a directory that all parties can access. The subject keeps the private key secret and uses it to decrypt the text encrypted by someone else using the corresponding public key (available in a public directory). Thus, others encrypt messages for the user with the user's public key, and the user decrypts it with his/her private key.

The steps involved in the PKI process are as follows:

1. The subject (user, company, or system) intending to exchange information securely applies for a certificate to the registration authority (RA).
2. The RA receives the request from the subject, verifies the subject's identity, and requests the CA to issue a public key certificate to the user.
3. The CA issues the public key certificate binding the subject's identity with the subject's public key; then, the updated information is sent to the validation authority (VA).
4. When a user makes a transaction, the user duly signs the message digitally using the public key certificate and sends the message to the client.
5. The client verifies the authenticity of the user by inquiring with the VA about the validity of the user's public key certificate.
6. The VA compares the public key certificate of the user with that of the updated information provided by the CA and determines the result (valid or invalid).

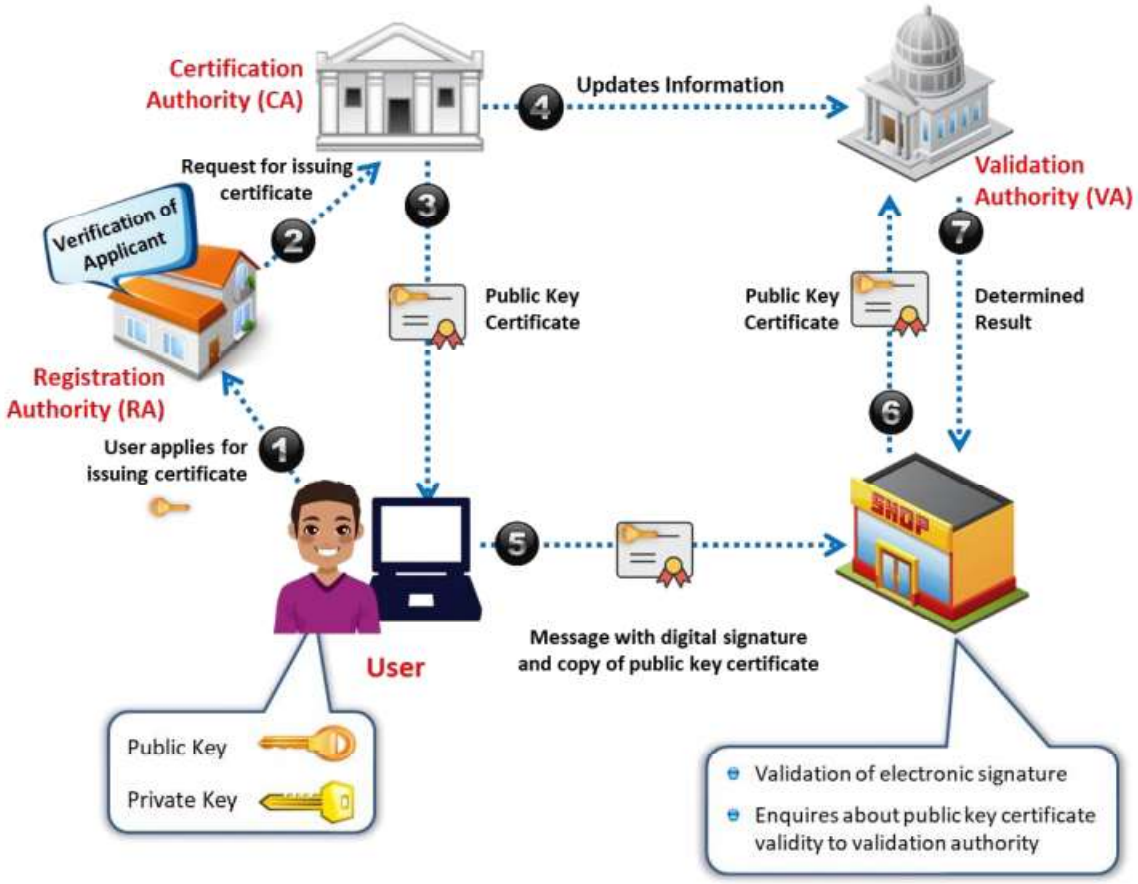
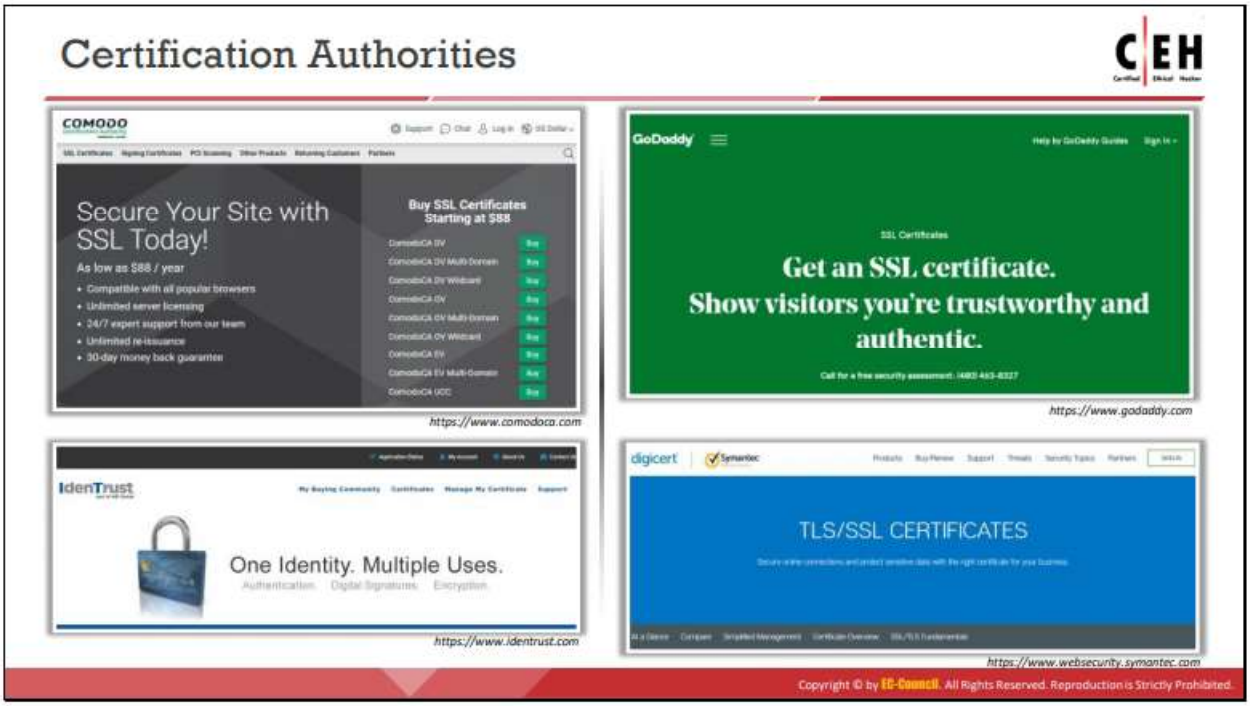


Figure 20.17: Public Key Infrastructure (PKI)



Certification Authorities

Certification authorities (CAs) are trusted entities that issue digital certificates. The digital certificate certifies the possession of the public key by the subject (user, company, or system) specified in the certificate. This aids others to trust signatures or statements made by the private key that is associated with the certified public key.

Some popular CAs are discussed below:

- **Comodo**

  Source: *https://www.comodoca.com*

  Comodo offers a range of PKI digital certificates with strong SSL encryption (128/256 available) with Server-Gated Cryptography (SGC). It ensures standards of confidentiality, system reliability, and pertinent business practices as judged via qualified independent audits. It offers PKI management solutions such as Comodo Certificate Manager and Comodo EPKI Manager.

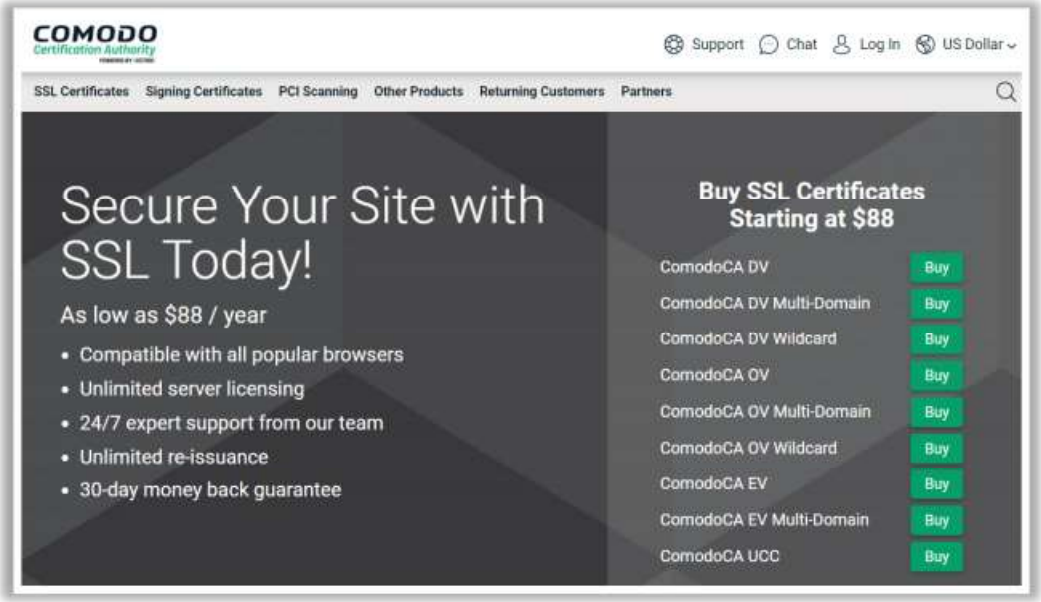


Figure 20.18: Screenshot of Comodo Website

- **IdenTrust**

  Source: *https://www.identrust.com*

  IdenTrust is a trusted third party that provides CA services for many sectors such as banks, corporates, governments, and healthcare. It provides solutions such as digital signing and sealing, compliance with NIST SP 800-171, global identity networks, and managed PKI hosting services.

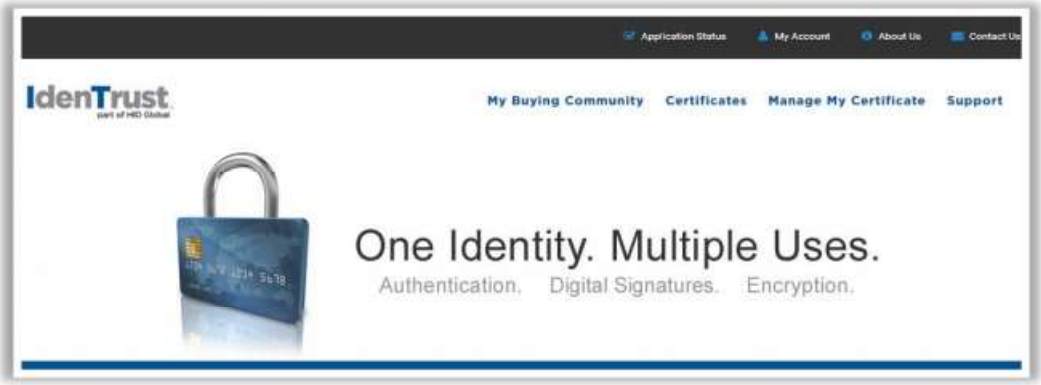


Figure 20.19: Screenshot of IdenTrust Website

- **Symantec**

  Source: *https://www.websecurity.symantec.com*

  Symantec Corporation (NASDAQ: SYMC) provides solutions that allow companies and consumers to engage in communications and commerce online with confidence. Symantec offers SSL/TLS certificates such as Secure Site, Secure Site with EV, and Secure Site Pro.

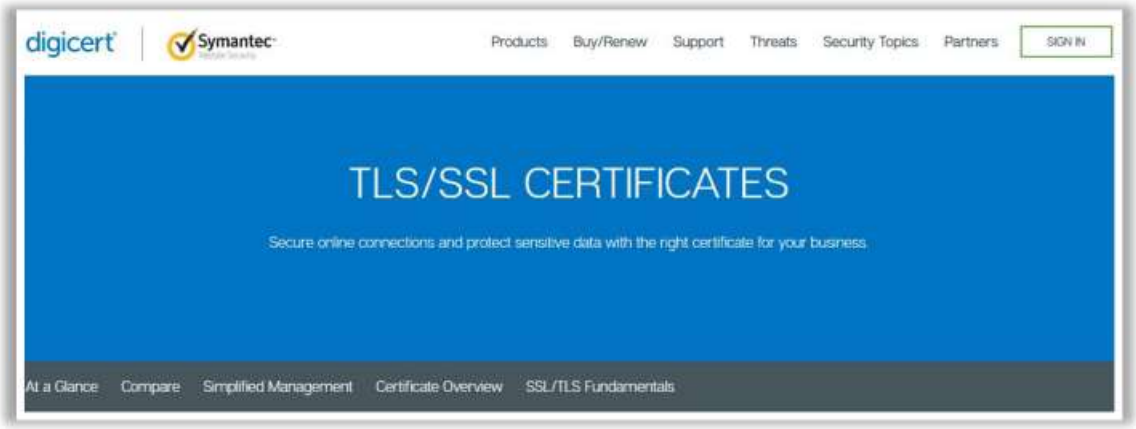


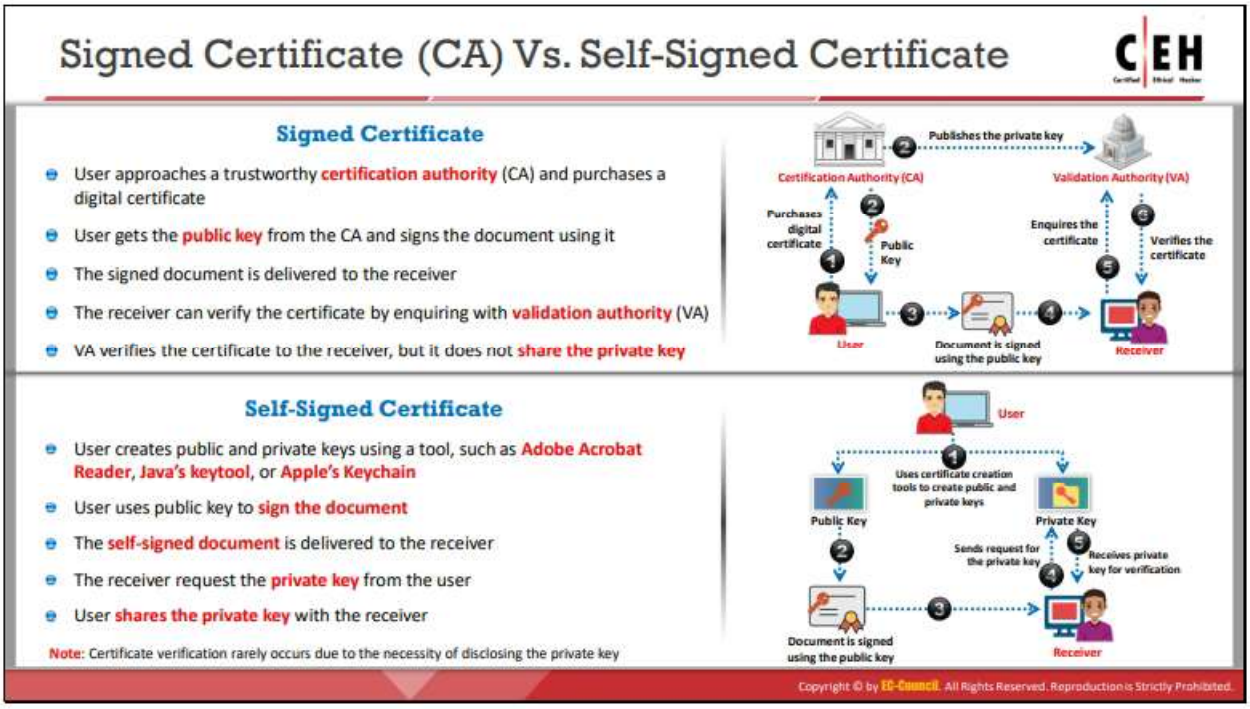
Figure 20.20: Screenshot of Symantec Website

- **GoDaddy**

  Source: *https://www.godaddy.com*

  GoDaddy SSL Certificates offer a complete range of certificates that comply with CA/Browser Forum guidelines. They provide the SHA-2 hash algorithm and 2048-bit encryption, protection of unlimited servers, etc.

Figure 20.21: Screenshot of GoDaddy Website



Signed Certificate (CA) vs. Self-Signed Certificate

- **Signed Certificate**

  CAs sign and issue signed certificates. These certificates contain a public key and the identity of the owner. The corresponding private key is not made publicly available; instead, it is kept secret by the authorized user. By issuing the certificate, the CA confirms or validates that the public key contained in the certificate belongs to the person, company, server, or other entity mentioned in the certificate. CA verifies an application's credentials; thus, users and relying parties trust the information in the CA's certificates. The CA accepts responsibility for saying, "Yes, this person is who they state they are, and we, the CA, certify that." Some popular CAs include Comodo, IdenTrust, Symantec, and GoDaddy.

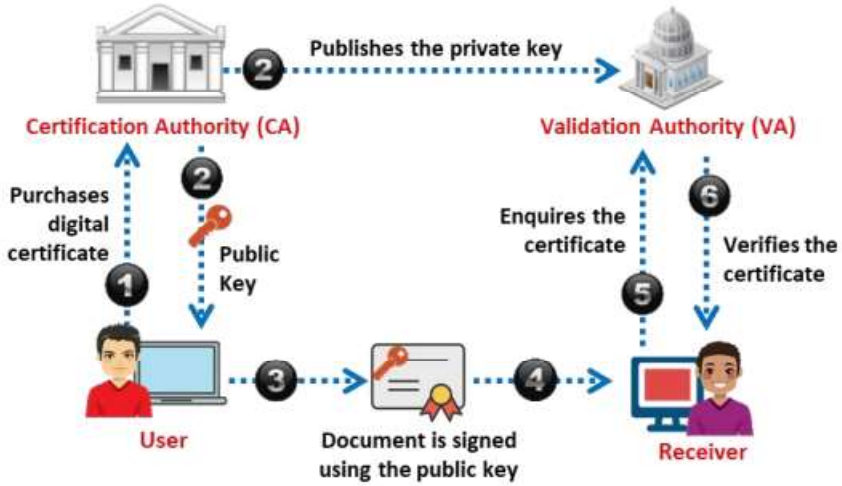


Figure 20.22: Process of obtaining signed certificates

As shown in the diagram above, the user approaches a trustworthy CA and purchases a digital certificate. The CA issues a certificate (having a public key and the identity of the user) to the user and updates the VA with the same information. The user signs a document with the public key and sends it to the receiver. Then, the receiver verifies the certificate by inquiring with the VA, who verifies the certificate to the receiver but does not share the private key.

- **Self-Signed Certificate**

A self-signed certificate is an identity certificate signed by the same entity whose identity it certifies. In general, self-signed certificates are widely used for testing servers. In a self-signed certificate, a user creates a pair of public and private keys using a certificate creation tool such as Adobe Acrobat Reader, Java's keytool, and Apple's Keychain, and signs the document with the public key. The receiver requests the sender for the private key to verify the certificate. However, certificate verification rarely occurs due to the necessity of disclosing the private key. This makes self-signed certificates useful only in a self-controlled testing environment.

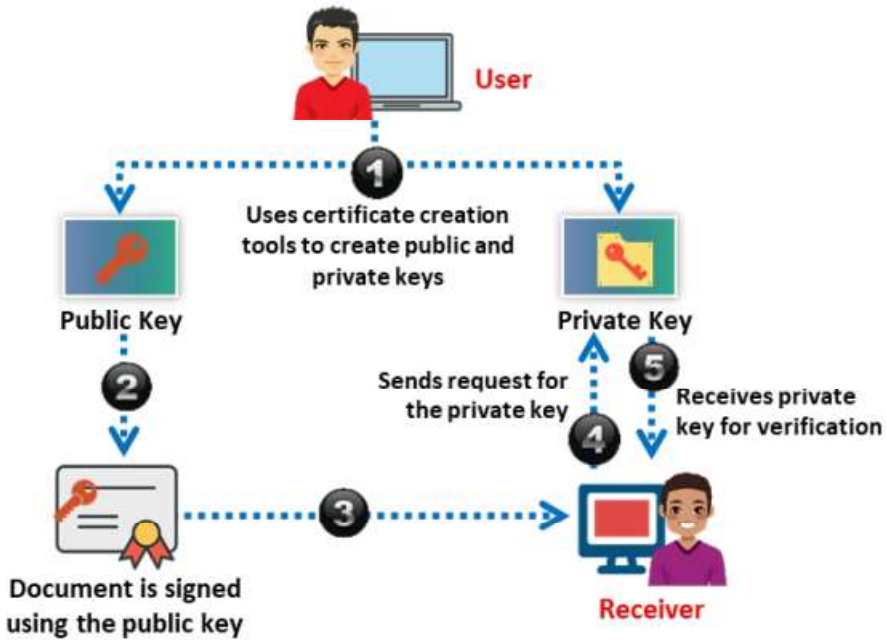
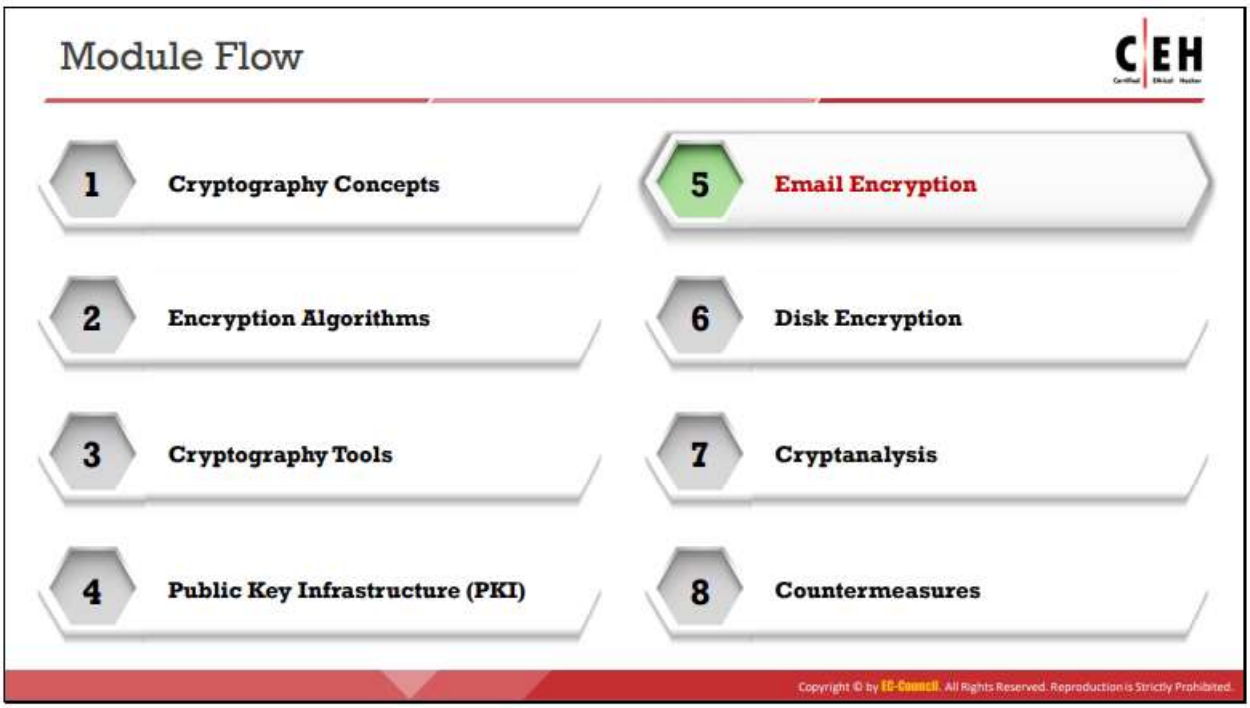
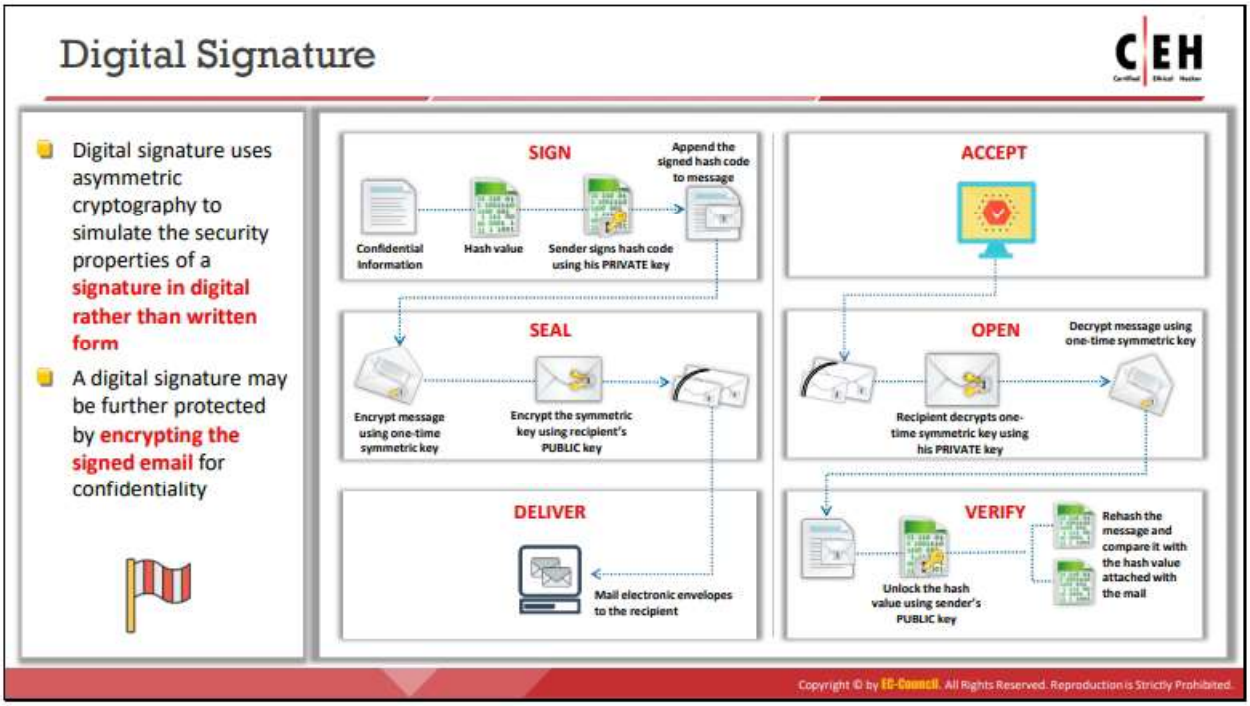


Figure 20.23: Process of generating self-signed certificates



Email Encryption

Currently, most businesses use email as the primary source of communication, as it is simple and easy to communicate or share information. Emails can contain sensitive information about the organization, such as projects, upcoming news, and financial data, which, when accessed by the wrong person, can cause severe losses to the organization. One can protect emails containing sensitive information by encrypting them. This section deals with email security mechanisms such as digital signature, SSL, TLS, cryptographic toolkits, PGP, GPG, and email encryption tools.



Digital Signature

A digital signature uses asymmetric cryptography to simulate the security properties of a signature in digital form rather than in written form. A digital signature is a cryptographic means of authentication. Public-key cryptography uses asymmetric encryption and helps the user to create a digital signature. The two types of keys in public-key cryptography are the private key (only the signer knows this key and uses it to create a digital signature) and the public key (it is widely known and the relying party uses it to verify the digital signature).

A hash function is an algorithm that helps a user to create and verify a digital signature. This algorithm creates a digital representation, also known as the message fingerprint. This fingerprint has a hash value that is much smaller than the message, but one that is unique to it. If the attacker changes the message, the hash function will automatically produce a different hash value.

To verify the digital signature, one needs the hash value of the original message and the encryption algorithm used to create the digital signature. Using both the public key and the new result, the verifier checks to see if the digital signature was created with the related private key and whether the new hash value is the same as the original one. A digital signature may be further protected by encrypting the signed email for confidentiality.

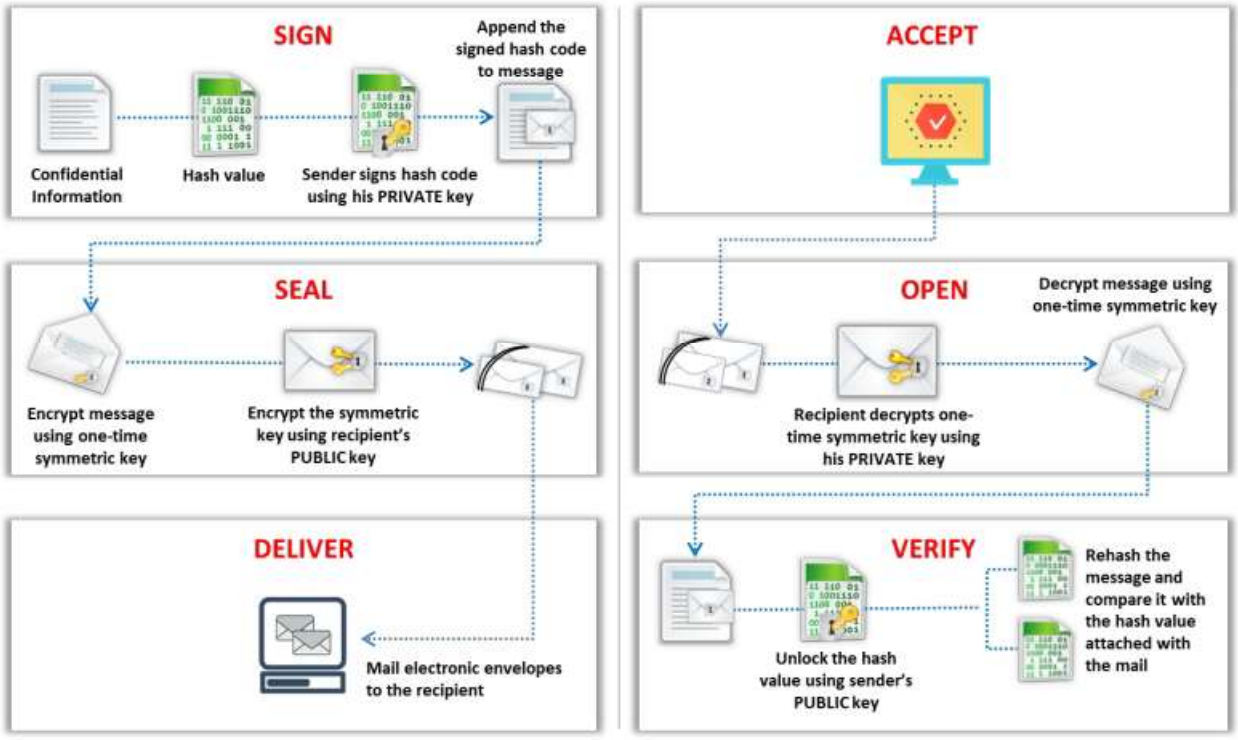
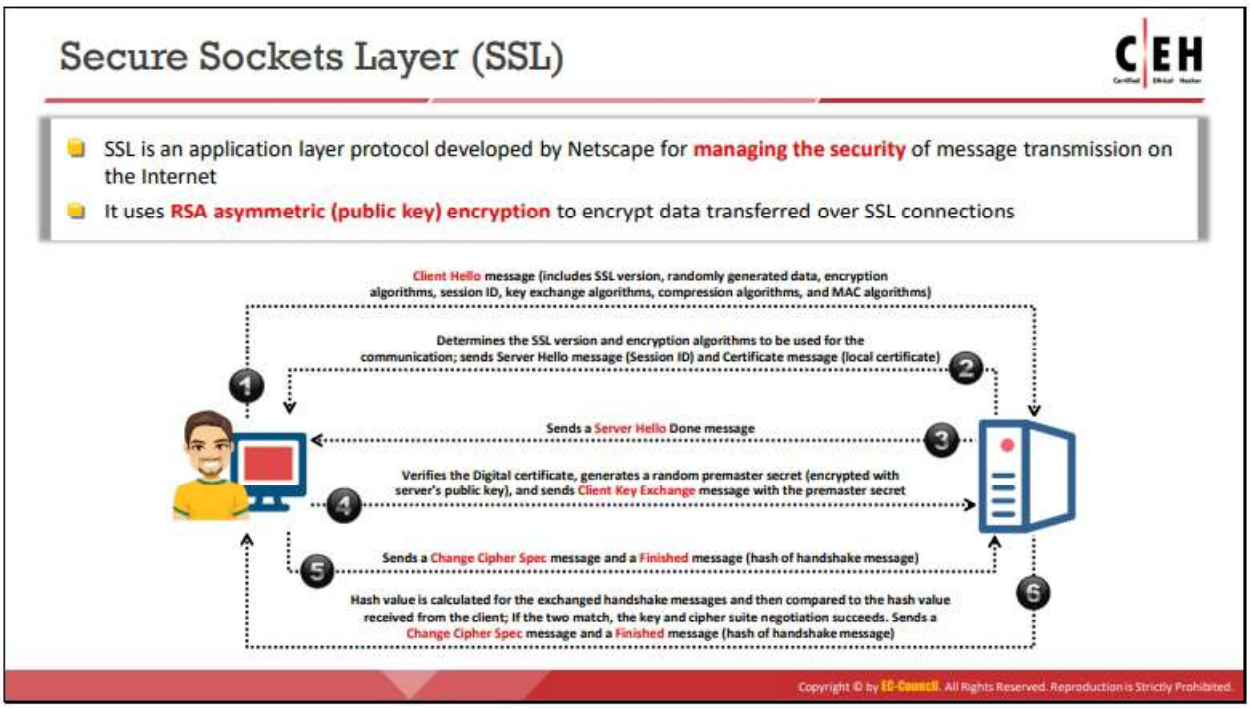


Figure 20.24: Using digital signature for email security



Secure Sockets Layer (SSL)

The Secure Sockets Layer (SSL) protocol is an application layer protocol developed by Netscape for managing the security of message transmission on the Internet. It is used to provide a secure authentication mechanism between two communicating applications, such as a client and a server. SSL requires a reliable transport protocol, such as TCP, for data transmission and reception. It uses RSA asymmetric (public-key) encryption to encrypt data transferred over SSL connections.

Any application-layer protocol that is higher than SSL, such as HTTP, FTP, and telnet, can form a transparent layer over SSL. SSL acts as an arbitrator between the encryption algorithm and the session key; it also verifies the destination server prior to the transmission and reception of data. SSL encrypts the complete data of the application protocol to ensure security.

SSL also offers "**channelsecurity**" with three basic properties:

- **Private channel** – All the messages are encrypted after a simple handshake is used to define a secret key.
- **Authenticated channel** – The server endpoint of the conversation is always encrypted, whereas the client endpoint is optionally authenticated.
- **Reliable channel** – Message transfer has an integrity check.

SSL uses both asymmetric and symmetric authentication mechanisms. Public-key encryption verifies the identities of the server, the client, or both. Once authentication has occurred, the client and server can create symmetric keys, allowing them to communicate and transfer data rapidly. An SSL session is responsible for carrying out the SSL handshake protocol to organize the states of the server and clients, thus ensuring consistency of the protocol.

SSL Handshake Protocol Flow

The SSL handshake protocol works on top of the SSL record layer. The processes executed in the three-way handshake protocol are as follows:

1. The client sends a hello message to the server, to which the server must respond with a hello message, or the connection will fail due to the occurrence of a fatal error. The attributes established due to the server and client hello are protocol version, session ID, cipher suite, and compression method.
2. After the connection is established, the server sends a certificate to the client for authentication. In addition, the server might send a server-key exchange message. On authentication of the server, it may ask the client for the certificate (if appropriate for the cipher suite selected).
3. The server sends a "hello done" message to inform the client that the handshake phase is complete and waits for the client's response.
4. If the client receives a certificate-request message, the client must respond to the message by sending a certificate message or "no certificate" alert. The server sends the client key-exchange message. The content of the message depends on the public-key algorithm between the server hello and the client hello. If the certificate sent by the client has signing ability, a digitally signed certificate verifies the message, and the client transmits it.
5. The client transmits the changed cipher-spec message and copies the pending cipher spec into the current cipher spec. The client sends a message to initiate the completion of the message under the new algorithm, keys, and secrets.
6. In response, the server replies by sending its own changed cipher-spec message, transfers the pending cipher spec to the current cipher spec, and initiates the completion of the message under the new cipher spec. At this point, the handshake is complete and the server starts exchanging the application-layer data.

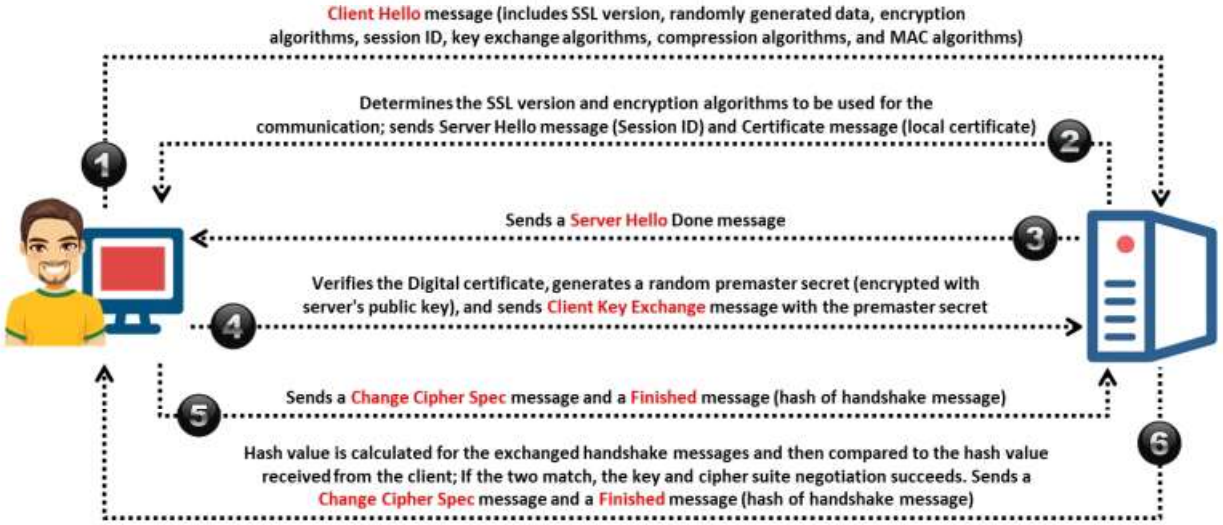
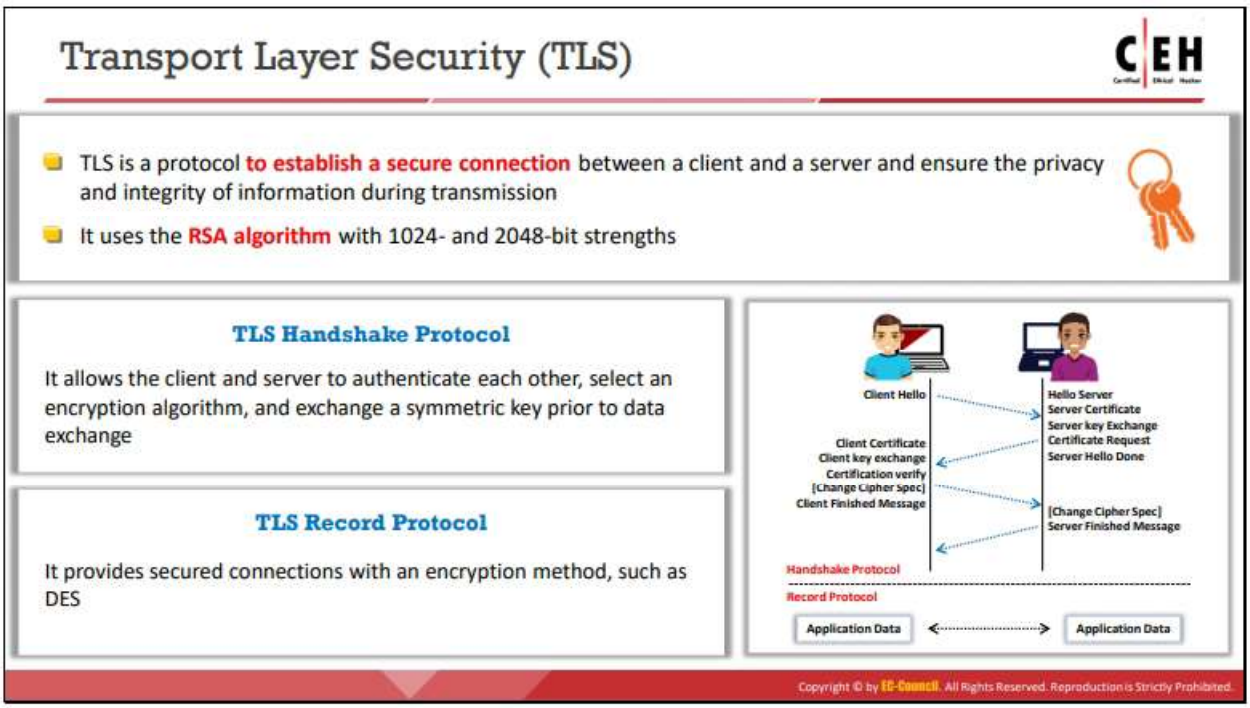


Figure 20.25: SSL handshake protocol flow

The resumption of a previous session or the replication of an existing session proceeds as follows:

- The client initiates the communication by sending a hello message with the session ID of the session that is to be resumed.
- If the server finds a match, it re-establishes the session under the specified session state with the same session ID.
- At this point, both the server and the client exchange the changed spec messages and proceed directly to the finished messages.
- After re-establishment, the server and client exchange data at the application layer.
- If the session ID does not exist, the server creates a new session ID. The SSL client and server then carry out a complete handshake.



Transport Layer Security (TLS)

The Transport Layer Security (TLS) protocol is used to establish a secure connection between a client and a server and ensure the privacy and integrity of information during transmission. It uses a symmetric key for bulk encryption, asymmetric key for authentication and key exchange, and message authentication codes for message integrity. It uses the RSA algorithm with strengths of 1024 and 2048 bits. Using TLS, one can reduce security risks such as message tampering, message forgery, and message interception. An advantage of TLS is that it is independent of the application protocol. Higher-level protocols can lie on top of TLS transparently.

TLS consists of two layers: TLS Record Protocol and TLS Handshake Protocol.

1. **TLS Record Protocol**

   The TLS Record Protocol is a layered protocol. It provides secured connections with an encryption method such as DES. It secures application data using the keys generated during the handshake and verifies its integrity and origin. The TLS Record Protocol provides connection security with two basic properties:

   - **The connection is private**: Uses symmetric cryptography for data encryption (e.g., DES). The protocol generates unique keys for symmetric encryption for each connection, depending on a secret negotiated by another protocol (such as the TLS Handshake Protocol). One can use the TLS Record Protocol without encryption.
   - **The connection is reliable**: It provides a message integrity check at the time of message transport using a keyed MAC. Secure hash functions (e.g., SHA, MD5) help to perform MAC computations.

The TLS Record Protocol does the following:

- Fragments outgoing data into manageable blocks and reassembles incoming data
- Optionally compresses outgoing data and decompresses incoming data
- Applies MAC to the outgoing data and uses MAC to verify the incoming data
- Encrypts outgoing data and decrypts incoming data

The TLS Record Protocol sends the outgoing encrypted data to the TCP layer for transport.

2. **TLS Handshake Protocol**

The TLS Handshake Protocol allows the client and server to authenticate each other and select an encryption algorithm and cryptographic keys prior to data exchange by the application protocol.

It provides connection security with three basic properties:

- The peer's identity can be authenticated using asymmetric cryptography. This can be made optional but is mostly required for at least one of the peers.
- The negotiation of a shared secret is secure.
- The negotiation is reliable.

The TLS Handshake Protocol operates on top of the TLS Record Protocol and is responsible for producing cryptographic parameters of the session state. At the start of communication, the TLS client and server agree on a protocol version, select cryptographic algorithms, optionally authenticate each other, and use asymmetric cryptography techniques to create shared secrets.

The steps involved in the TLS Handshake Protocol are as follows:

- Initially, the client sends a "Client hello" message accompanied by the client's random value and supported cipher suites to the server.
- The server responds to the client by sending a "Server hello" message accompanied by the server's random value.
- The server sends its certificate to the client for authentication and may request the client's certificate. The server sends the "Server hello done" message.
- The client sends its certificate to the server, if requested.
- The client generates a random pre-master secret and encrypts it with the server's public key; then, it sends the encrypted pre-master secret to the server.
- The server receives the pre-master secret. Thereafter, the client and server each create the master secret and session keys based on the pre-master secret.
- The client sends "Change cipher spec" to the server to indicate that it will start using the new session keys for hashing and encrypting messages. The client also sends "Clientfinished".

- The server receives "Changecipher spec" from the client and switches its record layer security state to symmetric encryption using the session keys. Then, the server sends "Serverfinished" to the client.
- Now, the client and server can exchange application data over the secure channel they have established, and all the messages exchanged between the client and server are encrypted using a session key.

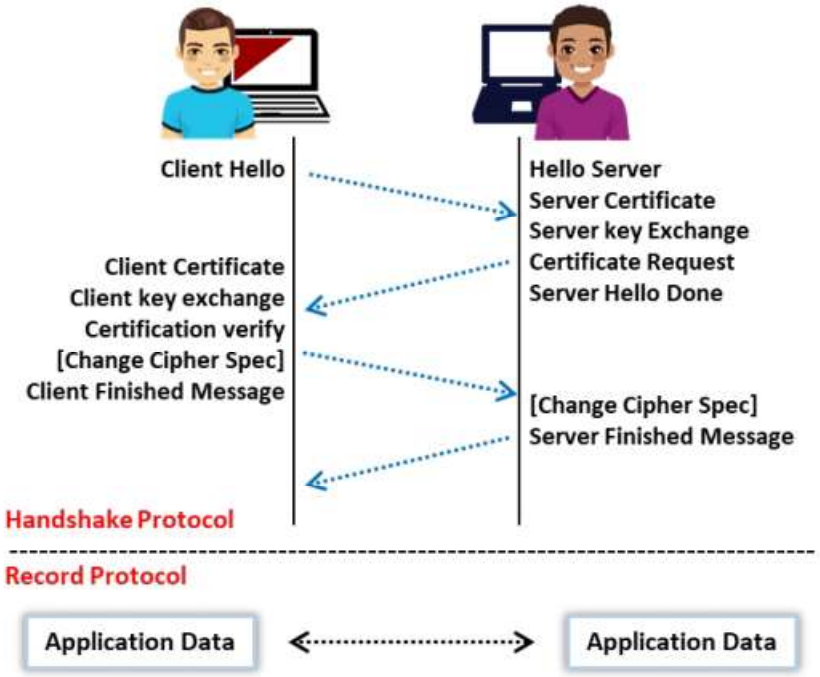
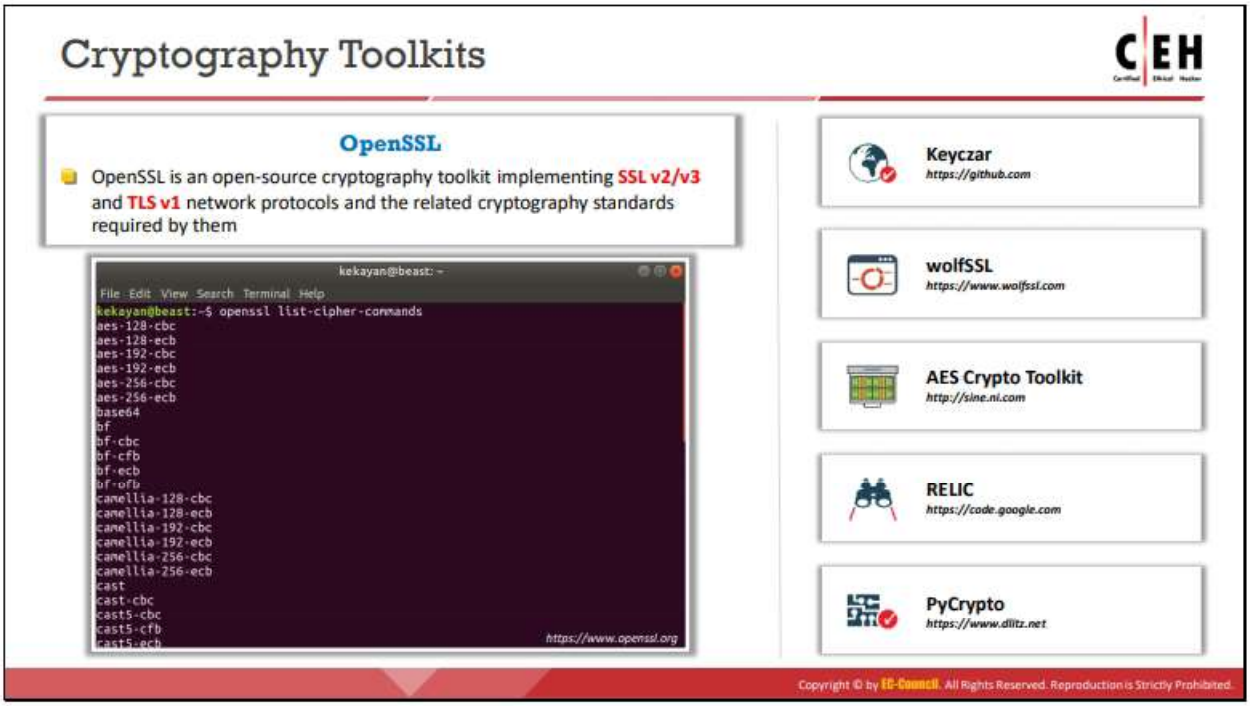


Figure 20.26: TLS handshake and record protocols



Cryptography Toolkits

Cryptography toolkits include cryptographic primitives, algorithms, and schemes used to provide security for various applications. Some cryptography toolkits are discussed below:

- **OpenSSL**

  Source: *https://www.openssl.org*

  OpenSSL is an open-source cryptography toolkit implementing the SSL and TLS network protocols and the related cryptography standards required by them. It is a command-line tool for using the various cryptography functions of OpenSSL's crypto-library from the shell. OpenSSL can be used for the creation and management of private keys, public keys, and parameters; public-key cryptographic operations; creation of X.509 certificates, CSRs, and CRLs; etc.

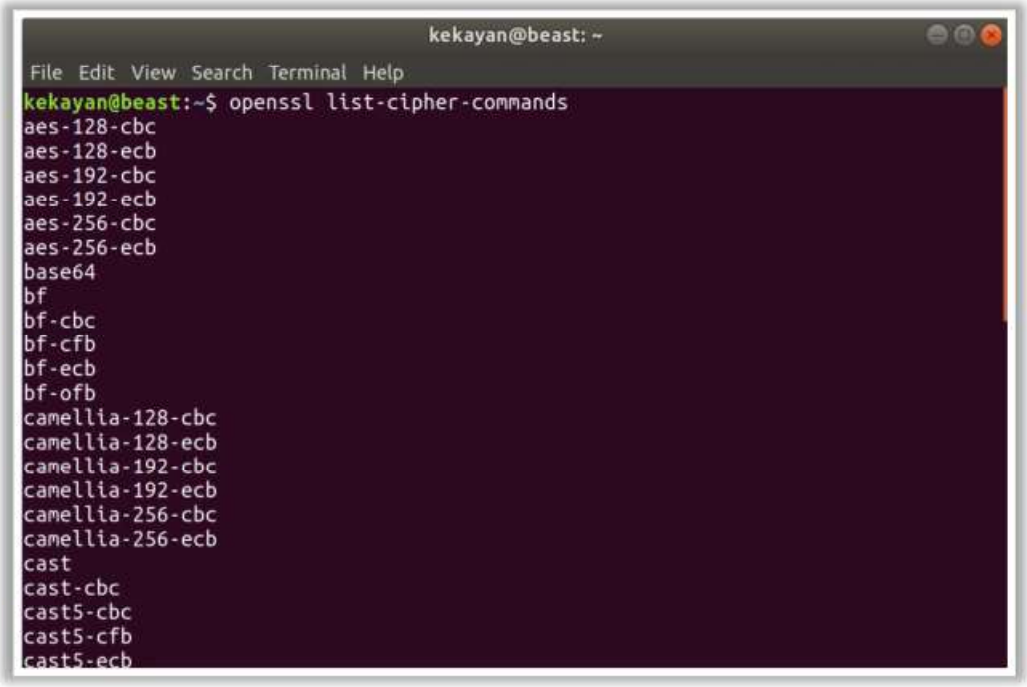
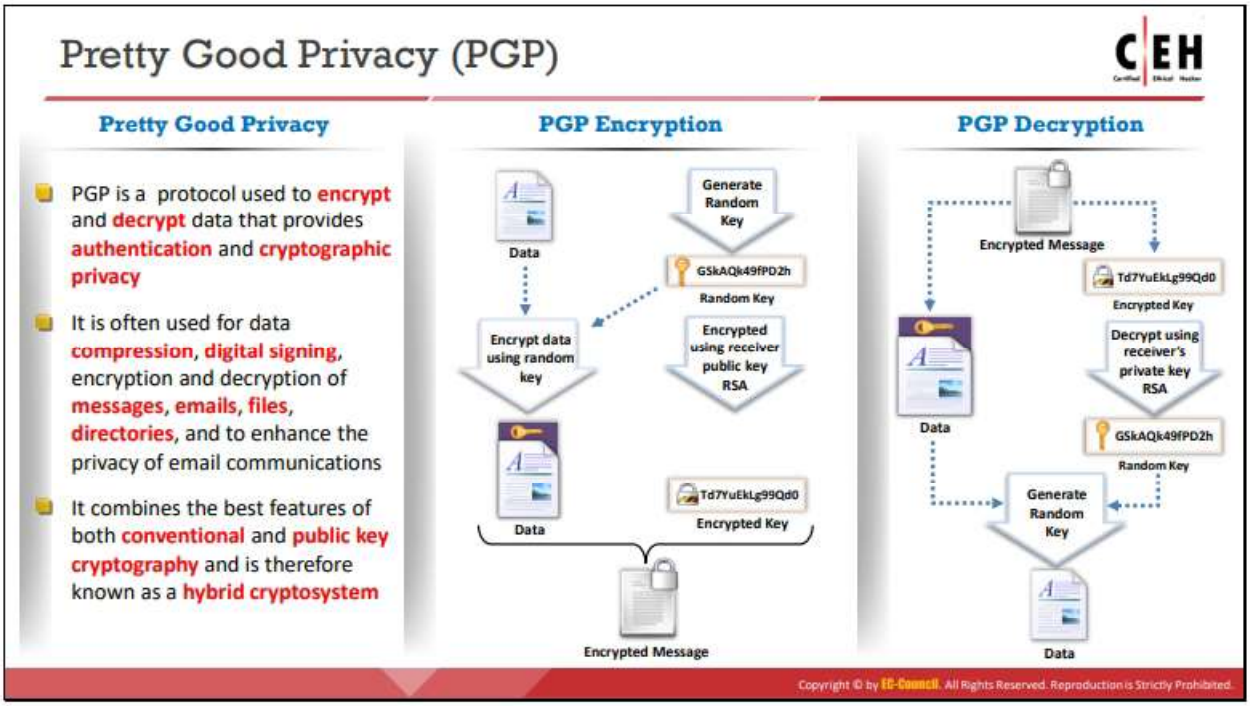


Figure 20.27: Screenshot of the OpenSSL command-line tool

Some additional cryptography toolkits are as follows:

- Keyczar (*https://github.com*)
- wolfSSL (*https://www.wolfssl.com*)
- AES Crypto Toolkit (*http://sine.ni.com*)
- RELIC (*https://code.google.com*)
- PyCrypto (*https://www.dlitz.net*)



Pretty Good Privacy (PGP)

Pretty Good Privacy (PGP) is a protocol used to encrypt and decrypt data with authentication and cryptographic privacy. It is often used for data compression, digital signing, encryption and decryption of messages, emails, files, and directories, and to enhance the privacy of email communications. The algorithm used for message encryption is RSA for key transport and IDEA for bulk-message encryption. PGP uses RSA for computing digital signatures and MD5 for computing message digests.

It combines the best features of both conventional (around 1,000 times faster than public-key encryption) and public-key cryptography (solution to key distribution and data transmission issues), and is therefore known as a hybrid cryptosystem.

PGP is used for:

- Encrypting a message or file prior to transmission so that only the recipient can decrypt and read it
- Clear signing of the plaintext message to ensure the authenticity of the sender
- Encrypting stored computer files so that no one besides the person who encrypted them can decrypt them
- Deleting files rather than just removing them from the directory or folder
- Data compression for storage or transmission

How PGP Works?

- **PGP Encryption**
  - When a user encrypts data with PGP, PGP first compresses the data.

Compressing the data reduces patterns in the plaintext that could be exploited by most cryptanalysis techniques to crack the cipher, thereby increasing the resistance to cryptanalysis considerably.

- PGP then creates a random key (GSkAQk49fPD2h) that is a one-time-only secret key.
- PGP uses the random key generated to encrypt the plaintext, resulting in a ciphertext.
- Once the data are encrypted, a random key is encrypted with the recipient's public key.
- The public-key-encrypted random key (Td7YuEkLg99Qd0) is sent along with the ciphertext to the recipient.

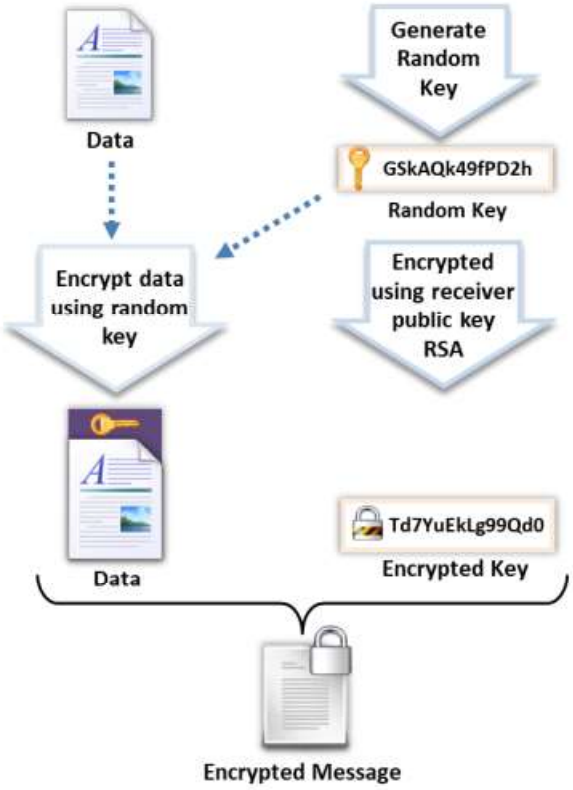


Figure 20.28: PGP Encryption

- **PGP Decryption**
  - Decryption works in reverse.
  - The recipient's copy of PGP uses his or her private key instead of the public key to recover the temporary random key.
  - PGP then uses the recovered random key to decrypt the conventionally encrypted ciphertext.

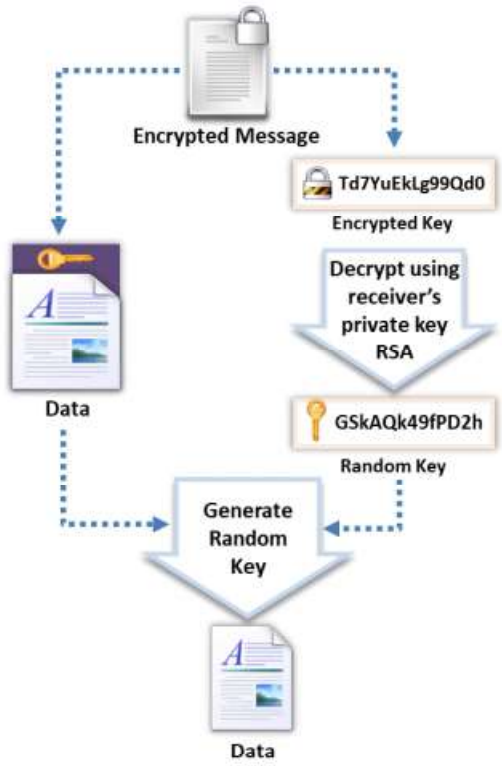
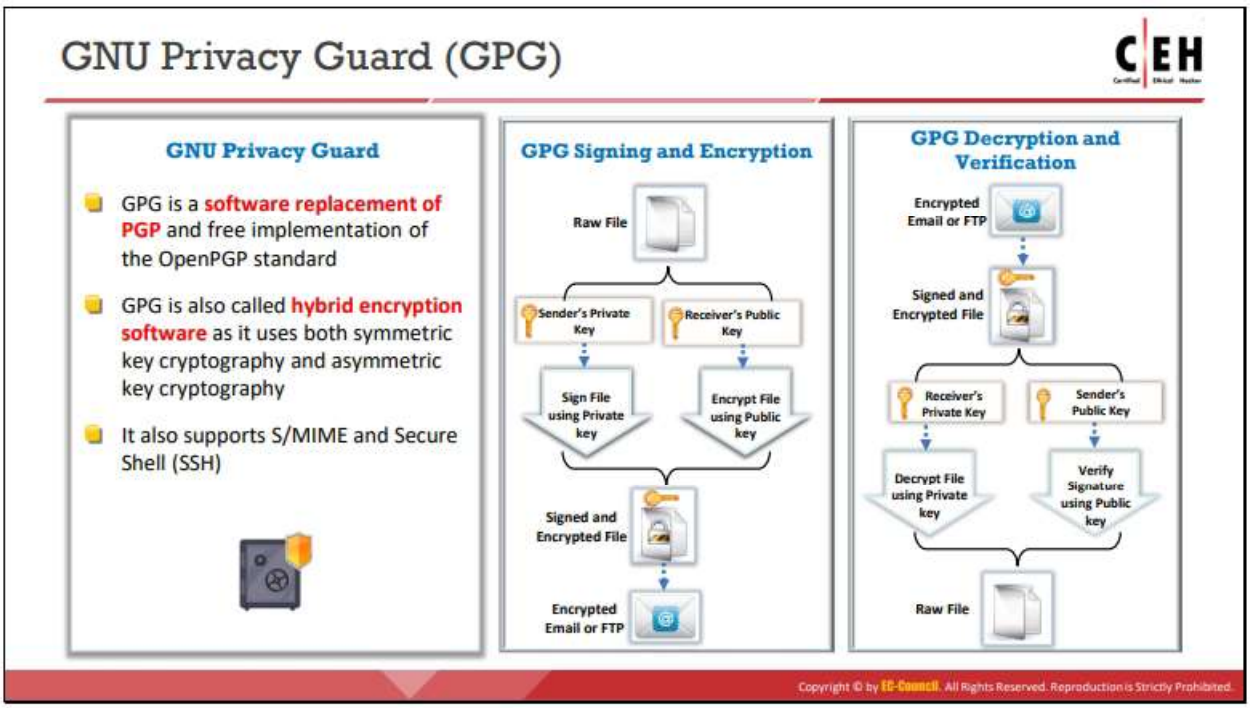


Figure 20.29: PGP Decryption

Note: Each step of the PGP encryption process (hashing, data compression, symmetric-key cryptography, and public-key cryptography) uses one of the various supported algorithms.



GNU Privacy Guard (GPG)

GNU Privacy Guard (GPG) is a software replacement of PGP and free implementation of the OpenPGP standard that is used to encrypt and decrypt data. GPG is also called a hybrid encryption software program, as it uses both symmetric-key cryptography and asymmetric-key cryptography for improved speed and secure key exchange, which is achieved using the receiver's public key for encrypting the session key.

GPG also supports S/MIME and Secure Shell (SSH). The latest version of GPG supports most cryptographic functions such as elliptic curve cryptography (ECDSA, ECDH, and EdDSA), and it also supports the cryptography library Libgcrypt.

GPG is used for the following:

- Proper key management of both private and public keys
- Creating new private keys and exporting or importing any key even though it is in some armored (e.g., ASCII) format
- Pushing the public key to the key server by signing code with the GPG key having a public signature
- Deleting a private key from local storage
- Encrypting and signing files using asymmetric keys for encrypting any file used for email or FTP
- Decrypting and verifying the encrypted file using asymmetric keys
- Detaching signatures where the signature file can be detached from the message file
- Managing and building the web of trust

- Automatically securing messages in messaging applications such as Psi and Fire

How GPG Works

- **GPG Encryption**
  - GPG encrypts messages individually by using asymmetric-key pairs.
  - The user sends the raw file, and GPG is used for signing the file using the sender's private key for confirming the file content at the time of signing.
  - Then, the file is encrypted using the receiver's public key. Now, the file can be decrypted only with the receiver's private key.
  - After encrypting the data, the encrypted file can be stored locally, distributed to the FTP servers, or sent to email recipients.

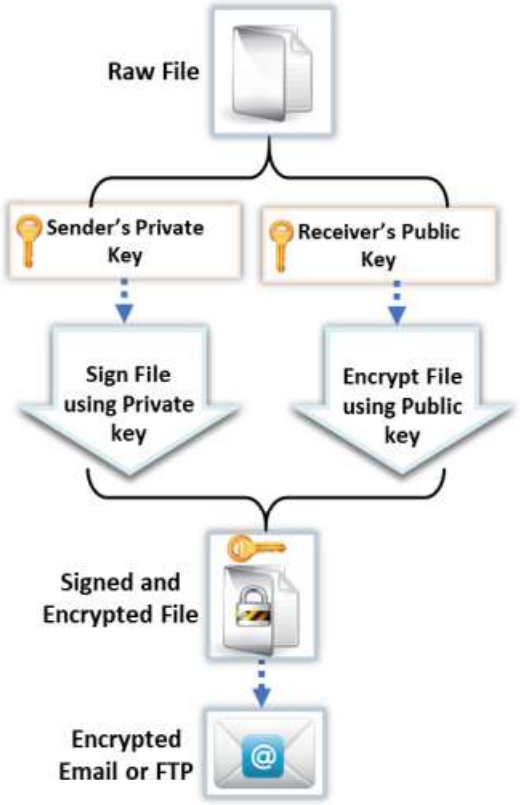


Figure 20.30: GPG Signing and Encryption

- **GPG Decryption**
  - GPG decryption is the reverse process of GPG encryption.
  - As the asymmetric-key pairs are used, GPG searches for the receiver's private key for decrypting the file.
  - Signature verification is done automatically by the GPG using the sender's public key after the decryption.

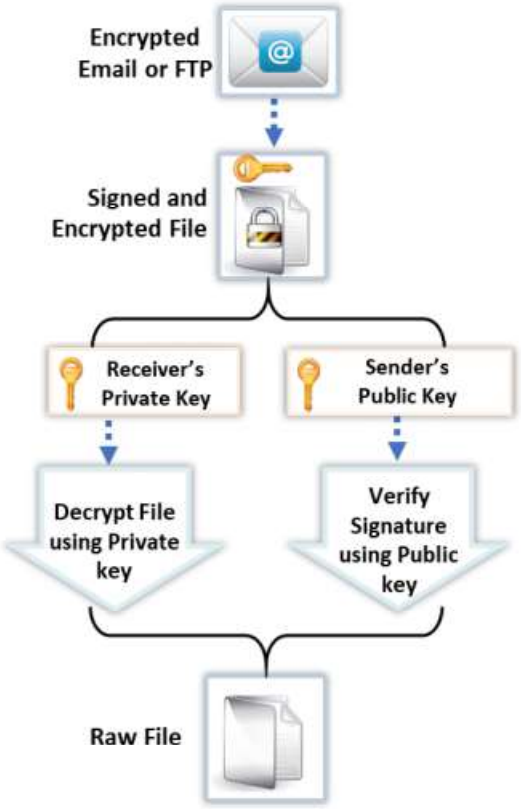
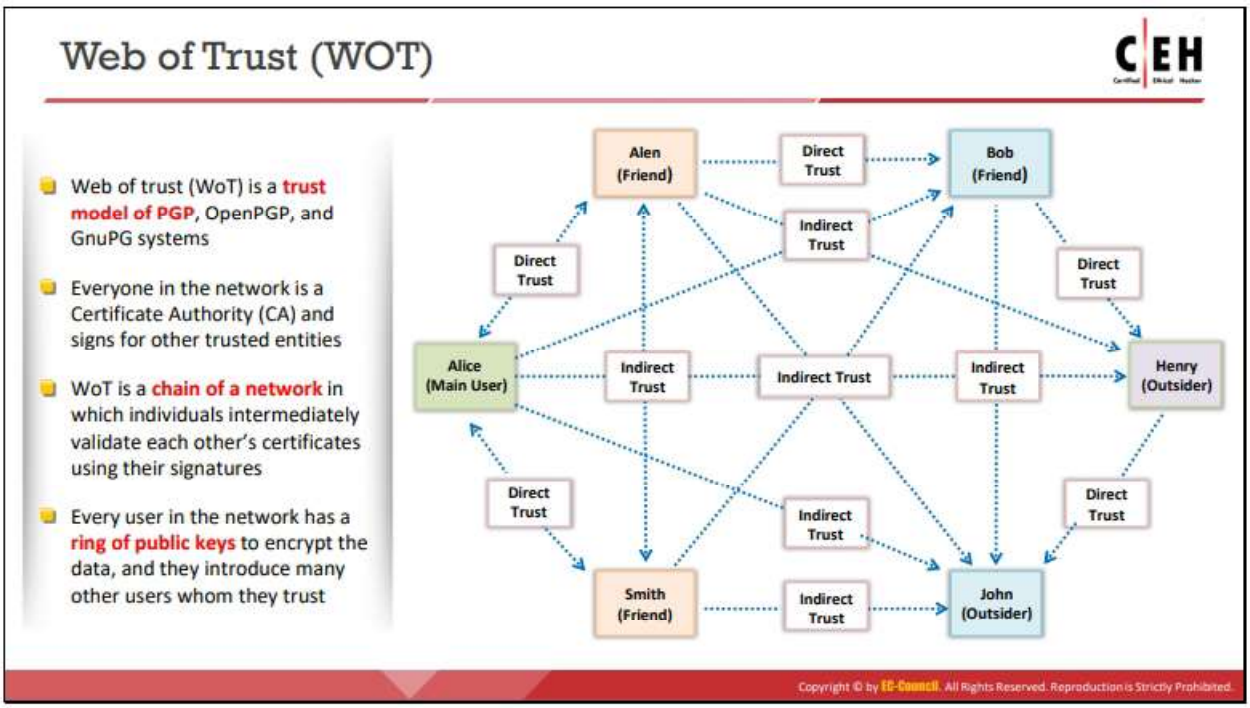


Figure 20.31: GPG Decryption and Verification



Web of Trust (WOT)

Web of trust (WoT) is a trust model of PGP, OpenPGP, and GnuPG accessible systems. It is an idea of decentralizing the key distribution among PGP users. In the PKI, only a centralized power such as the CA signs certificates in the network, ensuring authenticity between the public key and its owner. In WoT, everyone in the network is a CA, and they can sign for other trusted entities. WoT is a network chain in which individuals intermediately validate each other's certificates using their signatures. These signatures verify the ownership of keys from various trust levels. There is a bunch of similar trust levels through direct or indirect references in WoT.

Working of WOT

In WOT, every PGP user in the network has a ring of public keys to encrypt the data, and they introduce many other users whom they trust. In this trust model, a user encodes the data with the receiver's public key that is decrypted only by the receiver's private key. Then, every user in this model digitally signs the data with their private keys; when the recipient is validating it against the user's public key, he/she can confirm the user's authenticity. This process will ensure that data are received from a valid user without being modified, and only the intended user can access the information, as only he/she holds the related private key.

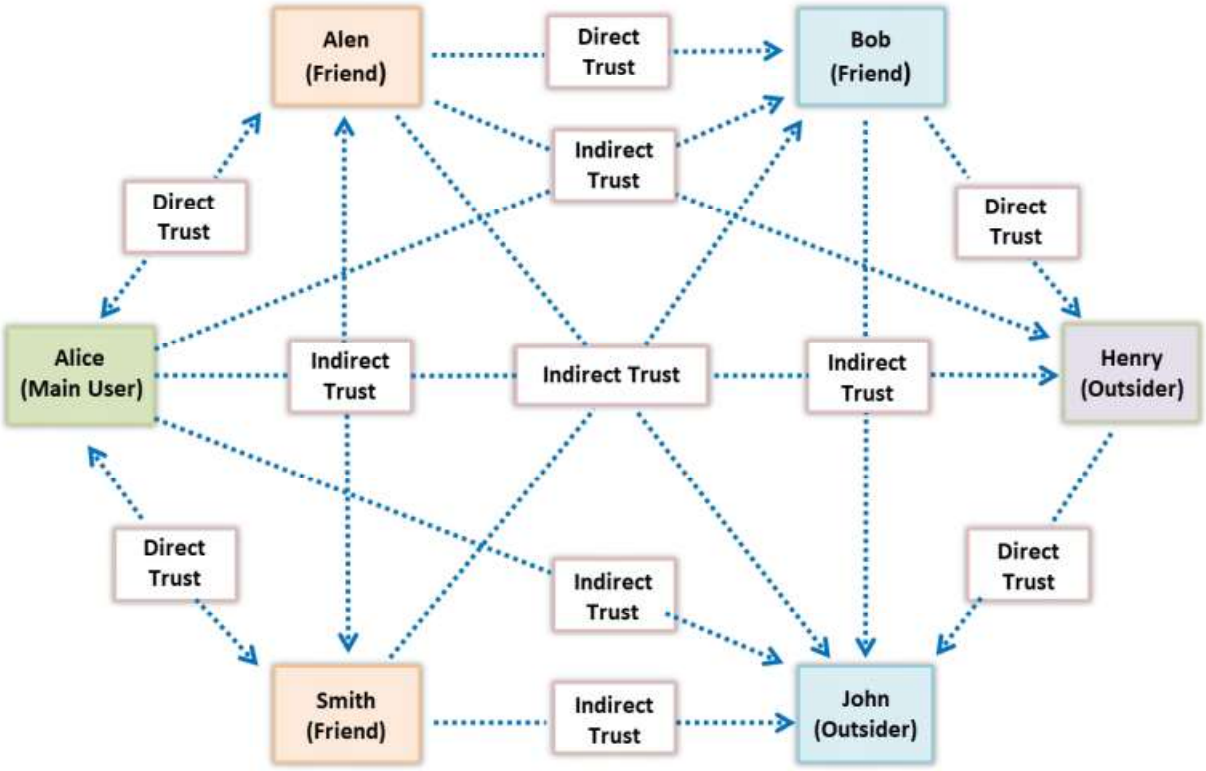
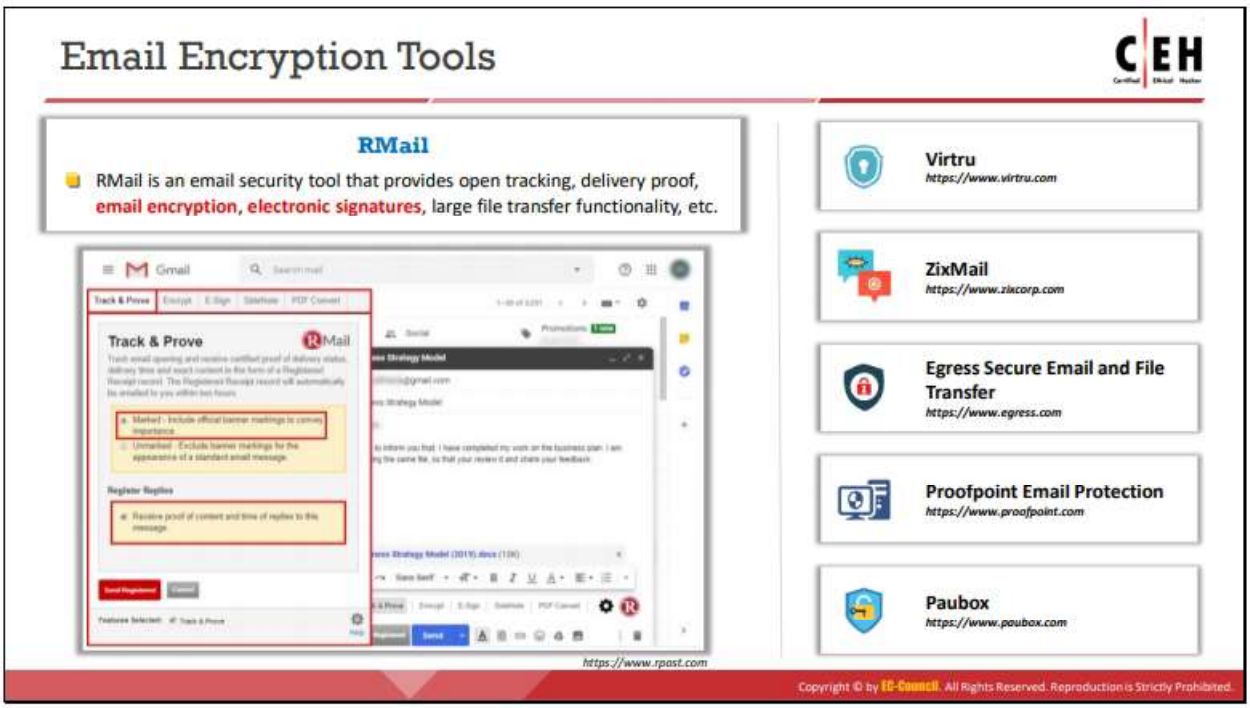


Figure 20.32: Working of WOT



Email Encryption Tools

Some important email encryption tools used to secure email messages are as follows:

- RMail

  Source: *https://www.rpost.com*

  RMail is an email security tool that provides open tracking, delivery proof, email encryption, electronic signatures, large file transfer functionality, etc. RMail works seamlessly with users' existing email platforms, including Microsoft Outlook, Gmail, etc. Using this tool, you can encrypt sensitive emails and attachments for security or legal compliance.

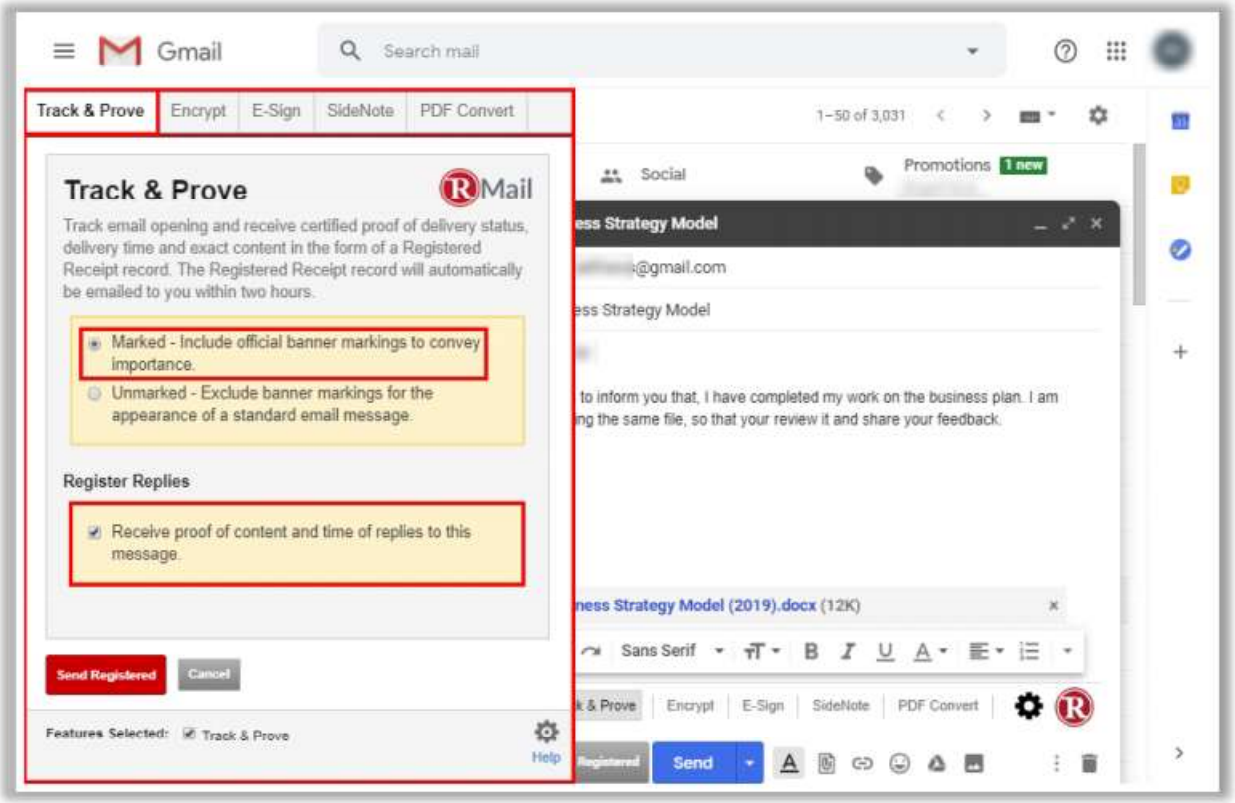
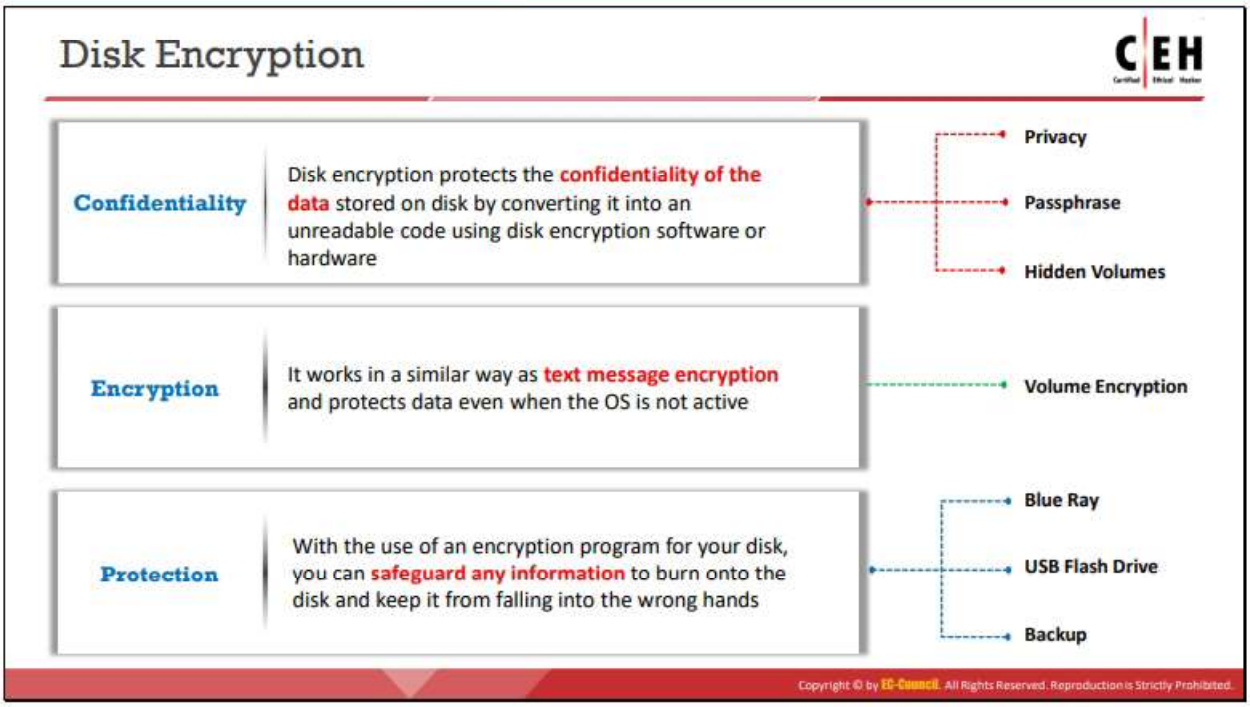


Figure 20.33: Screenshot of RMail

Some additional email encryption tools are as follows:

- Virtru (*https://www.virtru.com*)
- ZixMail (*https://www.zixcorp.com*)
- Egress Secure Email and File Transfer (*https://www.egress.com*)
- Proofpoint Email Protection (*https://www.proofpoint.com*)
- Paubox (*https://www.paubox.com*)



Disk Encryption

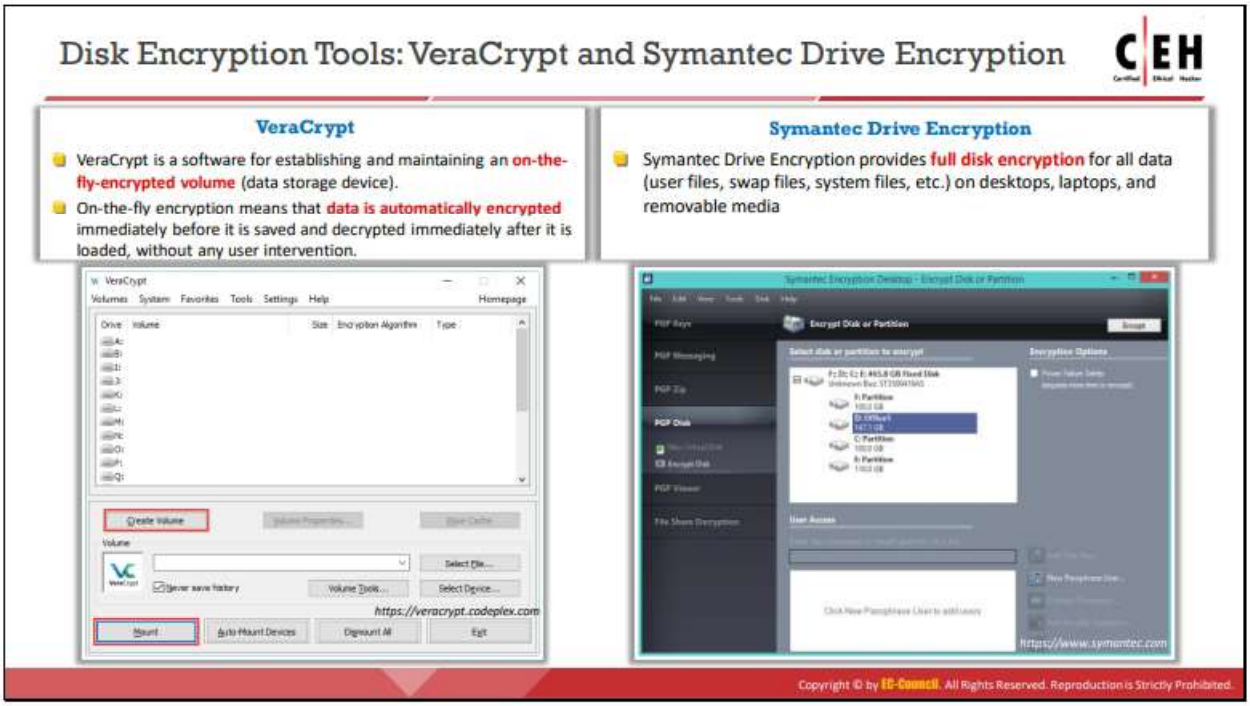
Disk encryption encrypts every bit of data stored on a disk or a disk volume, thus preventing illegal access to data storage. This section deals with disk encryption concepts and various disk encryption tools.

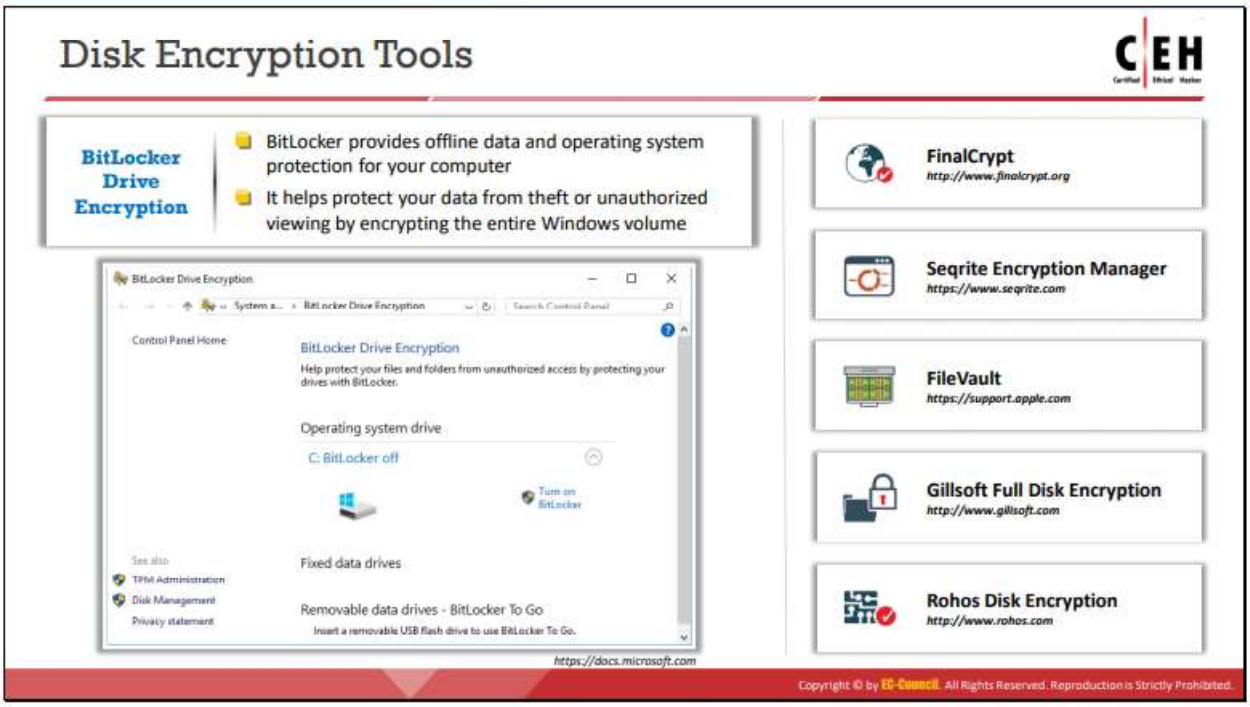
Disk encryption is a technology that protects the confidentiality of the data stored on a disk by converting it into an unreadable code using disk encryption software or hardware, thus

preventing unauthorized users from accessing it. Disk encryption provides confidentiality and privacy using passphrases and hidden volumes.

Disk encryption works similarly to text-message encryption and protects data even when the OS is not active. By using an encryption program for one's disk (Blue Ray, DVD, USB flash drive, external HDD, backup), one can safeguard any or all information on the disk and prevent it from falling into the wrong hands. Disk-encryption software scrambles the information on the disk into an illegible code. It is only after decryption of the disk information that one can read and use it.

Disk encryption is useful when the user needs to physically send sensitive information. In addition, disk encryption can protect the real-time exchange of information from compromising threats. When users exchange encrypted information, the chances of compromising the information are minimized. The only way an attacker can access the information is by decrypting the message. Furthermore, encryption software installed on a user's system ensures the security of the system. Install encryption software on any system that holds valuable information or systems that are exposed to unlimited data transfer.





Disk Encryption Tools

The common goal of disk encryption tools is to encrypt a disk partition to provide confidentiality to the information stored on it. Some disk encryption tools are discussed below.

- **VeraCrypt**

  Source: *https://www.veracrypt.fr*

VeraCrypt is a software for establishing and maintaining an on-the-fly-encrypted volume (data storage device). On-the-fly encryption means that data is automatically encrypted just before it is saved and decrypted just after it is loaded without any user intervention. No data stored on an encrypted volume can be read (decrypted) without using the correct password/keyfile(s) or correct encryption keys. The entire file system is encrypted (e.g., file names, folder names, free space, metadata, etc.).

Files can be copied to and from a mounted VeraCrypt volume just like they are copied to/from any normal disk (e.g., by simple drag-and-drop operations). Files are automatically decrypted on the fly (in memory/RAM) while they are read or copied from an encrypted VeraCrypt volume. Similarly, files that are written or copied to the VeraCrypt volume are automatically encrypted on the fly (just before they are written to the disk) in RAM.

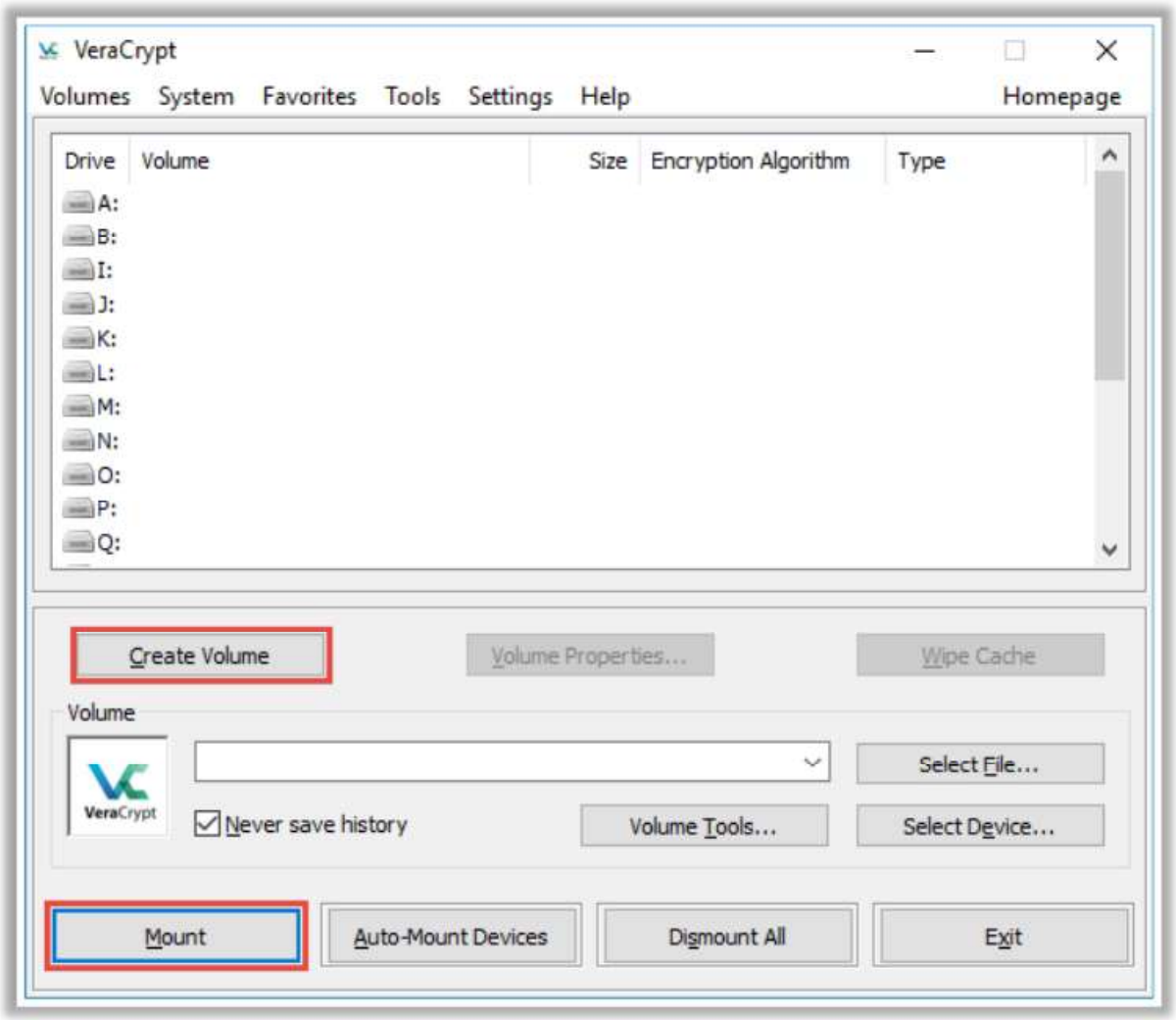


Figure 20.34: Screenshot of VeraCrypt

- **Symantec Drive Encryption**

  Source: *https://www.symantec.com*

  Symantec Drive Encryption (formerly PGP Whole Disk Encryption) provides organizations with complete, transparent drive encryption for all data (user files, swap files, system files, hidden files, etc.) on laptops, desktops, and removable media. It protects data from unauthorized access, thereby providing strong security for intellectual property as well as customer and partner data. Symantec Encryption Management Server can centrally manage the protected systems, as it simplifies deployment, policy creation, distribution, and reporting.

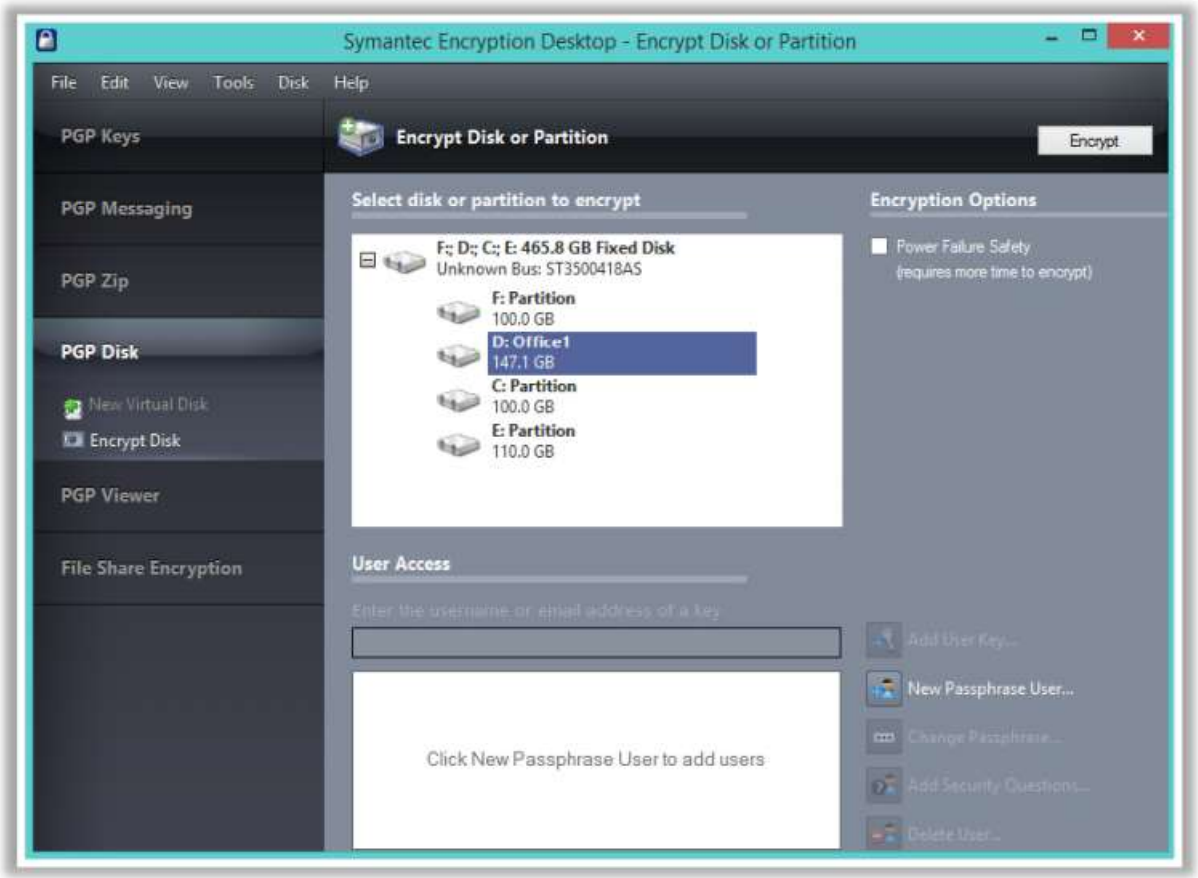


FIGURE 20.35: Screenshot of Symantec Drive Encryption

- **BitLocker Drive Encryption**

  Source: *https://docs.microsoft.com*

  BitLocker provides offline-data and OS protection for your computer. It helps ensure that data that is stored on a computer that is running Windows® is not revealed if the computer is tampered with when the installed OS is offline. BitLocker uses a microchip that is called a Trusted Platform Module (TPM) to provide enhanced protection for your data and to preserve early boot-component integrity. The TPM can help protect your data from theft or unauthorized access by encrypting the entire Windows volume.

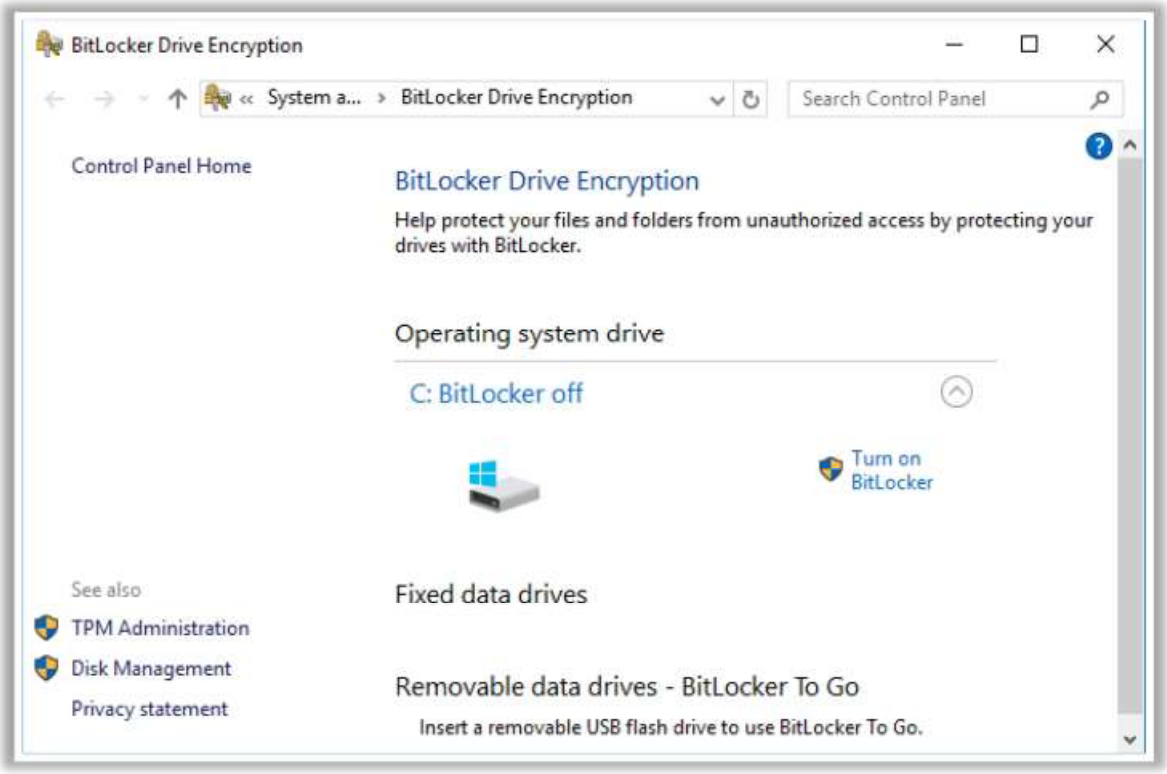


Figure 20.36: Screenshot of BitLocker Drive Encryption

Some additional disk encryption tools are as follows:

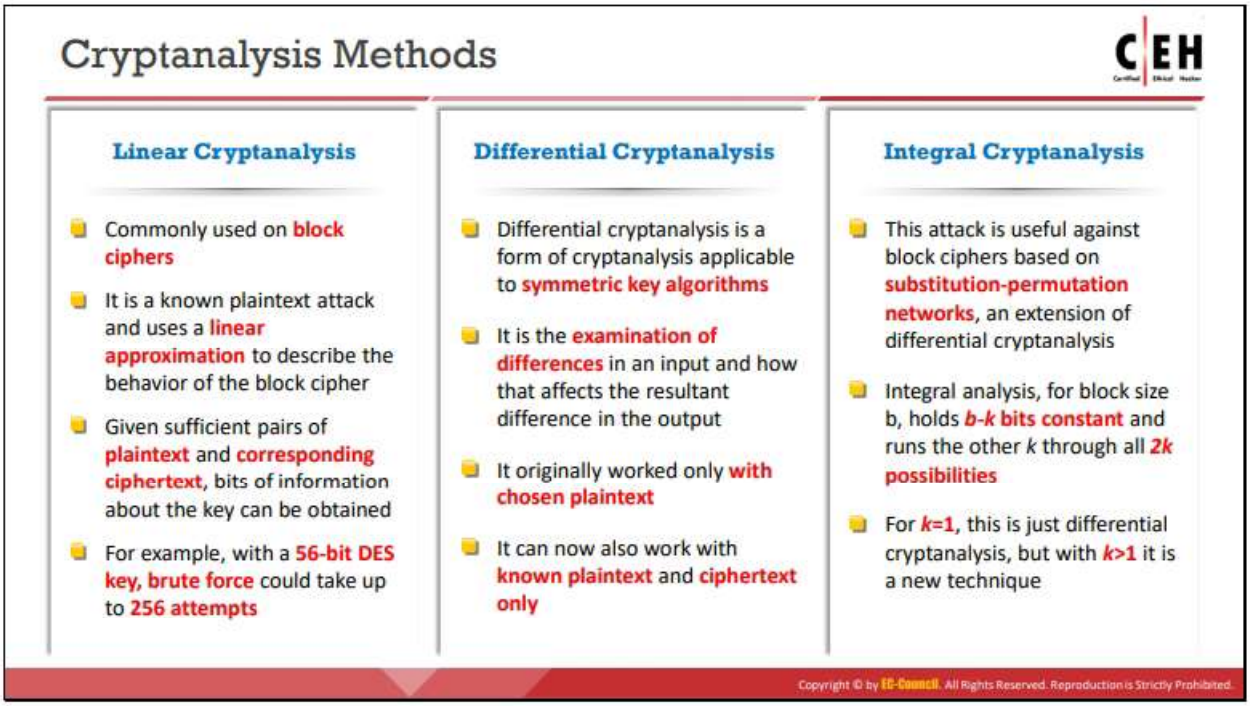
- FinalCrypt (*http://www.finalcrypt.org*)
- Seqrite Encryption Manager (*https://www.seqrite.com*)
- FileVault (*https://support.apple.com*)
- Gillsoft Full Disk Encryption (*http://www.gilisoft.com*)
- Rohos Disk Encryption (*http://www.rohos.com*)

Cryptanalysis

Attackers may implement various cryptography attacks to evade the security of a cryptographic system by exploiting vulnerabilities in code, ciphers, cryptographic protocols, or key management schemes. This process is known as cryptanalysis.

Cryptanalysis is the study of ciphers, ciphertext, or cryptosystems with the ability to identify vulnerabilities in them and thus extract plaintext from ciphertext even if the cryptographic key or algorithm used to encrypt the plaintext is unknown.

This section deals with various cryptography attacks that an attacker performs to compromise cryptographic systems as well as various cryptanalysis techniques and tools that help in breaching cryptographic security.



Cryptanalysis Methods

- **Linear Cryptanalysis**

  Linear cryptanalysis is based on finding affine approximations to the action of a cipher. It is commonly used on block ciphers. This technique was invented by Mitsarue Matsui. It is a known plaintext attack and uses a linear approximation to describe the behavior of the block cipher. Given sufficient pairs of plaintext and corresponding ciphertext, bits of information about the key can be obtained. Obviously, the more pairs of plaintext and ciphertext one has, the greater are the chances of success.

  Remember that cryptanalysis is an attempt to crack cryptography. For example, with the 56-bit data encryption standard (DES), **key brute-forcing could take up to 256 attempts**. Linear cryptanalysis require 2^{43} known plaintexts. This is better than brute-forcing but is still impractical in most situations. The math may be a bit complex for novice cryptographers, but let us look at the basics of it.

  With this method, a linear equation expresses the equality of two expressions, which consists of XORed binary variables. For example, the following equation XORs the sum of the first and third plaintext bits, and the first ciphertext bit is equal to the second bit of the key:

  $$P_1 \oplus P_3 \oplus C1 = K_2$$

  You can use this method to slowly re-create the key that was used.

  After doing this for each bit, you will have an equation of the form

  $$P_{i1} \oplus P_{i2} \oplus \ldots \oplus C_{j1} \oplus C_{j2} \oplus \ldots = K_{k1} \oplus K_{k2} \oplus \ldots$$

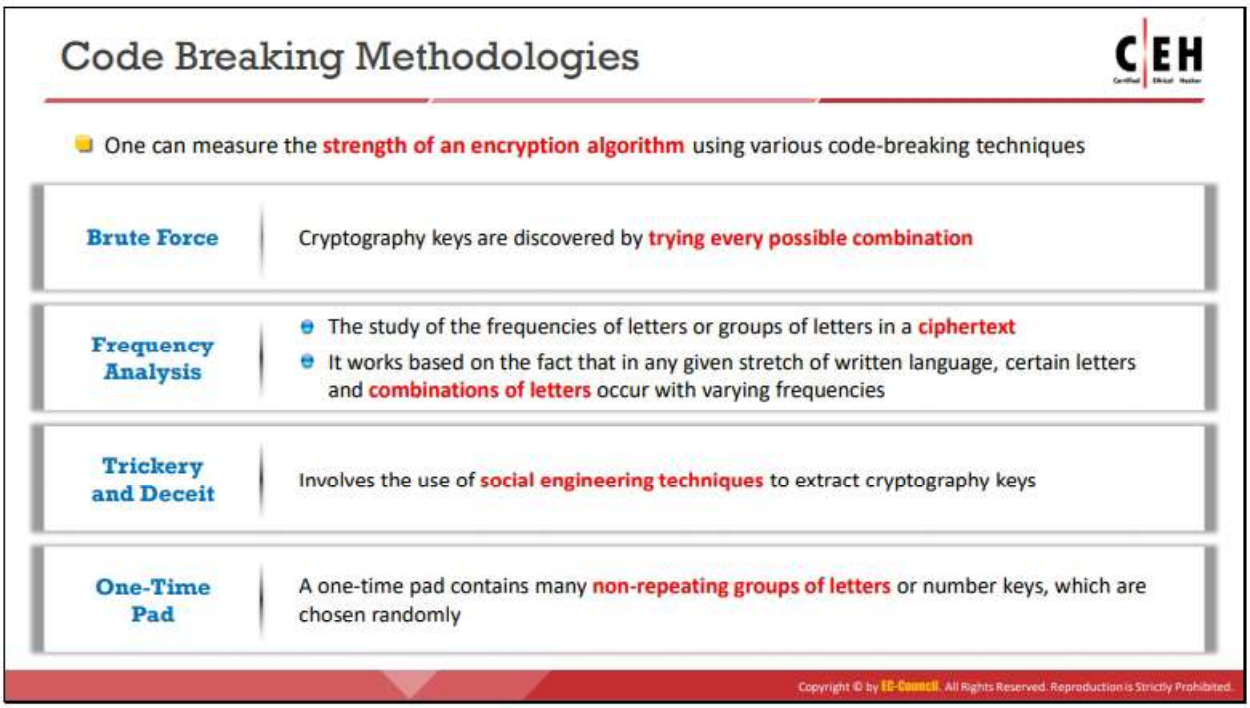
You can then use **Matsui's Algorithm 2**, using known plaintext-ciphertext pairs, to guess the values of the key bits involved in the approximation. For each set of values of the key bits on the right-hand side (referred to as a partial key), count how many times the approximation holds true over all the known plaintext-ciphertext pairs; call this count T. The partial key whose T has the greatest absolute difference from half the number of plaintext-ciphertext pairs is designated as the most likely set of values for those key bits.

- **Differential Cryptanalysis**

  Differential cryptanalysis is a form of cryptanalysis applicable to symmetric-key algorithms. It was invented by Eli Biham and Adi Shamir. Essentially, it is the examination of differences in input and how that affects the resultant difference in the output. It originally worked only with chosen plaintext. It can also work with known **plaintext** and **ciphertext**.

- **Integral Cryptanalysis**

  Integral cryptanalysis was first described by Lars Knudsen. This attack is particularly useful against block ciphers based on substitution-permutation networks as an extension of differential cryptanalysis. The differential analysis looks at pairs of inputs that differ in only one bit position, with all other bits being identical. Integral analysis for block size b holds b-k bits constant and runs the other k bits through all 2k possibilities. For k = 1, this is just differential cryptanalysis, but with k > 1, it is a new technique.



Code Breaking Methodologies

One can measure the strength of an encryption algorithm using various code breaking techniques, some of which are as follows:

- **Brute Force**

  Code breakers or cryptanalysts work to recover the plaintext of a message without knowing the required key in advance. They may first try to recover the key, or they may go after the message itself. A common cryptanalytic technique is a brute-force attack, or exhaustive search, in which the keys are determined by trying every possible combination of characters.

  The efficiency of a brute-force attack depends on the hardware configuration. The use of faster processors means that more keys will be tested per second. Cryptanalysts carried out a successful brute-force attack on a DES encryption method, which effectively rendered DES obsolete.

- **Frequency Analysis**

  Frequency analysis is the study of the frequency of letters or groups of letters in a ciphertext. Frequency analysis of letters and words is another method used to crack ciphers. It works on the principle that, in any given stretch of written language, certain letters and combinations of letters occur with varying frequencies. This technique examines the number of times that a particular symbol appears in a ciphertext. For example, the letter "**e**" is a common letter in the English language. If the letter "**k**" appears commonly in a ciphertext, it can be reasonably concluded that "**k**" in the encrypted language is equivalent to "**e**" in English.

Encrypted source code is more vulnerable to these types of attacks because words such as "**#define**," "**struct,**" "**else,**" and "**return**" are repeated frequently in code. Sophisticated cryptosystems are required to maintain the security of messages against frequency analysis.

- **Trickery and Deceit**

  Trickery and deceit require a high level of mathematical and cryptographic skills. It involves the use of social engineering techniques to extract cryptography keys.

  Example: It is fairly easy to decrypt an entire message if the user knows some of its content.

  An attacker can use social engineering techniques to trick or bribe someone to encrypt and send a known message, which, when intercepted, could then be easily decrypted using standard cryptanalysis techniques.

- **One-Time Pad**

  One can crack any cipher if provided with sufficient time and resources. However, there is an exception called a one-time pad, which users assume to be unbreakable even with infinite resources.

  A one-time pad mostly contains a non-repeating set of letters or numbers, which the system chooses randomly. The user writes them on small sheets of paper and then pastes them together in a pad.

  Example of One-time pad usage:

  The sender encrypts only one plaintext character using each key letter on the pad, and the receiver decrypts each letter of the ciphertext using an identical pad. Once the letter uses a page, he or she tears it off the pad and securely discards it; hence, the name one-time pad.

  Drawback:

  The key length is the same as that of the message, thus making it impossible to encrypt and send large messages.

Cryptography Attacks

Cryptography attacks are based on the assumption that the cryptanalyst has access to the **encrypted information**

Ciphertext-only Attack	Attacker has access to the cipher text; the goal of this attack is to **recover the encryption key** from the ciphertext
Adaptive Chosen-plaintext Attack	Attacker makes a **series of interactive queries**, choosing subsequent plaintexts based on the information from the previous encryptions
Chosen-plaintext Attack	Attacker **defines their own plaintext**, feeds it into the cipher, and analyzes the resulting ciphertext
Related-Key Attack	Attacker can obtain ciphertexts encrypted under **two different keys**; this attack is useful if the attacker can obtain the plaintext and matching cipher text
Dictionary Attack	Attacker constructs a **dictionary of plaintext** along with its corresponding ciphertext that they have learnt over a certain period of time

Cryptography Attacks (Cont'd)

Known-plaintext Attack	Attacker has **knowledge of some part of the plain text**; using this information, the key used to generate ciphertext is deduced to decipher other messages
Chosen-ciphertext Attack	Attacker obtains plaintexts corresponding to an **arbitrary set** of ciphertexts of their own choosing
Rubber Hose Attack	Extraction of cryptographic secrets (e.g., the password to an encrypted file) from a person by **coercion or torture**
Chosen-key Attack	Attacker usually breaks an **n bit** key cipher into $2^{n/2}$ operations
Timing Attack	It is based on repeatedly measuring the **exact execution times** of modular exponentiation operations
Man-in-the-middle Attack	Attacker performs this attack on the **public key cryptosystems** where key exchange is required before communication takes place

Cryptography Attacks

Attackers conduct cryptography attacks by assuming that the cryptanalyst has access to the encrypted information. A cryptography attack or cryptanalysis involves the study of various principles and methods of decrypting the ciphertext back to the plaintext without knowledge of the key.

The various types of cryptography attacks are as follows:

- **Ciphertext-only Attack**

  Ciphertext-only is less effective but much more likely for the attacker. The attacker only has access to a collection of ciphertexts. This is much more likely than known plaintext but is also the most difficult. The attack is completely successful if the corresponding plaintexts (or even better, the key) can be deduced. The ability to obtain any information at all about the underlying plaintext is still considered a success. So what does the attacker do with the ciphertexts he/she has accumulated? You can analyze them for patterns, trying to find something that would give you a hint as to the key that was used to crack them. Often, the result of this attack is just a partial break and not a complete break.

- **Adaptive Chosen-plaintext Attack**

  In this type of attack, an attacker has complete access to the plaintext message including its encryption, and he/she can also modify the content of the message by making a series of interactive queries, choosing subsequent plaintext blocks based on the information from the previous encryption queries and functions. To perform this attack, an attacker needs to interact with the encryption device.

- **Chosen-plaintext Attack**

  A chosen plaintext attack is a highly effective type of cryptanalysis attack. In this attack, the attacker obtains the ciphertexts corresponding to a set of plaintexts of his/her own choosing. This allows the attacker to attempt to derive the key used and thus decrypt other messages encrypted with that key. Basically, since the attacker knows the plaintext and the resultant ciphertext, he/she gains many insights into the key used. This technique can be difficult but is not impossible.

- **Related-Key Attack**

  The related-key attack is similar to the chosen plaintext attack, except that the attacker can obtain ciphertexts encrypted under two different keys. This is actually a very useful attack if you can obtain the plaintext and matching ciphertext. The attack requires that the differing keys be closely related, e.g., in a wireless environment where subsequent keys might be derived from previous keys. Then, while the keys are different, they are close. Much like the ciphertext-only attack, this type of attack is most likely only going to yield a partial break.

- **Dictionary Attack**

  In this attack, the attacker constructs a dictionary of plaintext along with its corresponding ciphertext that he/she has analyzed and obtained for a certain period of time. After building the dictionary, if the attacker obtains the ciphertext, he/she uses the already built dictionary to find the corresponding plaintext. Attackers use this technique to decrypt keys, passwords, passphrases, and ciphertext.

- **Known-plaintext Attack**

  In this attack, the only information available to the attacker is some plaintext blocks along with the corresponding ciphertext and algorithm used to encrypt and decrypt the text. Using this information, the key used to generate the ciphertext is deduced so as to decipher other messages. This attack works on block ciphers and is an example of linear cryptanalysis. The known plaintext blocks are generated using a series of intelligent guesses and logic, and not by accessing the plaintext over a channel.

- **Chosen-ciphertext Attack**

  The attacker obtains the plaintexts corresponding to an arbitrary set of ciphertexts of his own choosing. Using this information, the attacker tries to recover the key used to encrypt the plaintext. To perform this attack, the attacker must have access to the communication channel between the sender and the receiver.

  There are two variants of this attack:

  - Lunchtime or Midnight Attack: In this attack, the attacker can have access to the system for only a limited amount of time or can access only a few plaintext-ciphertext pairs.
  - Adaptive Chosen-ciphertext Attack: In this attack, the attacker selects a series of ciphertexts and then observes the resulting plaintext blocks.

- **Rubber Hose Attack**

  Attackers extract cryptographic secrets (e.g., the password to an encrypted file) from a person by coercion or torture. In general, people under pressure cannot maintain security, and they will reveal secrets or hidden information. Attackers torture victims to reveal secret keys or passwords used to encrypt the information.

- **Chosen-key Attack**

  In this type of attack, an attacker not only breaks a ciphertext but also breaks into a larger system, which is dependent of that ciphertext. The attacker usually breaks an n-bit key cipher into $2^{n/2}$ operations. Once an attacker breaks the cipher, he gets access to the system, and he can control the whole system, access confidential data, and perform further attacks.

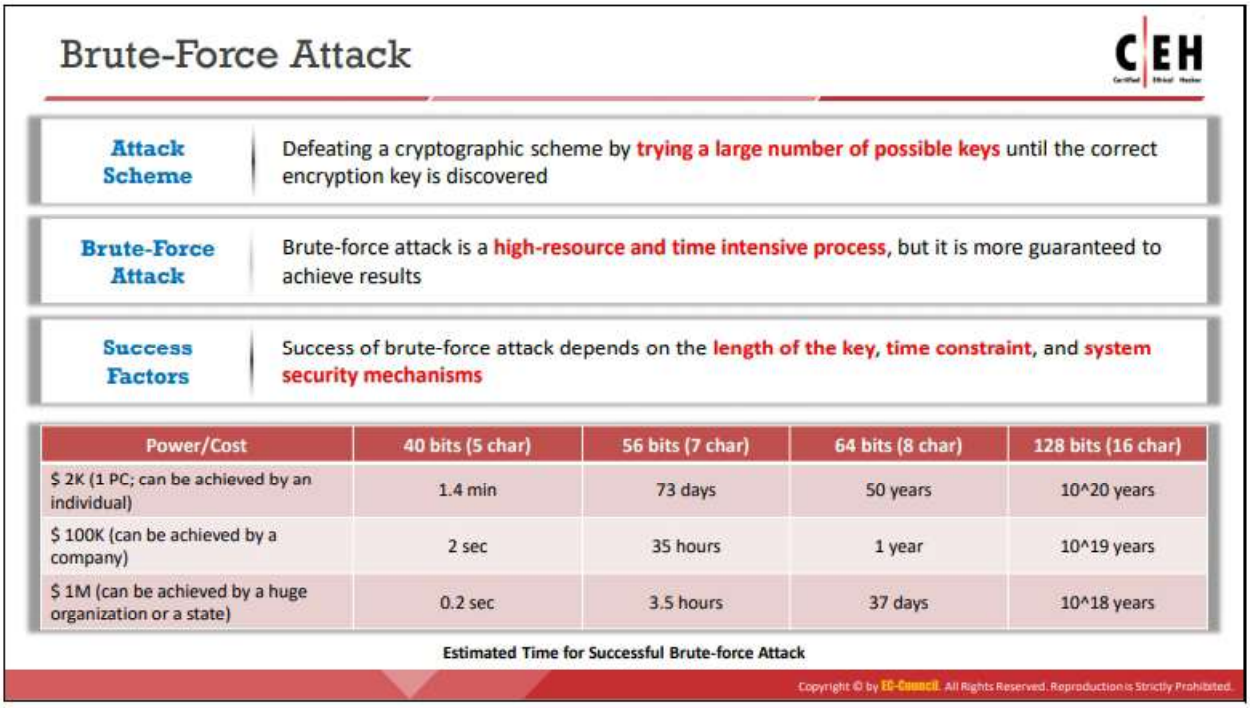
- **Timing Attack**

  It is based on repeatedly measuring the exact execution times of modular exponentiation operations. The attacker tries to break the ciphertext by analyzing the time taken to execute the encryption and decryption algorithm for various inputs. In a computer, the time taken to execute a logical operation may vary based on the input given. An attacker tries to extract the plaintext by giving varying inputs.

- **Man-in-the-Middle Attack**

  This attack is performed against a cryptographic protocol. Here, an attacker intercepts the communication between a client and a server and negotiates the cryptographic

parameters. Using this attack, an attacker can decrypt the encrypted content and obtain confidential information such as system passwords. An attacker can also inject commands that can modify the data in transit. The attacker usually performs an MITM attack on public-key cryptosystems where key exchange is required before communication takes place.



Brute-Force Attack

It is extremely difficult to crack cryptographic systems, as they have no practical weaknesses to exploit; however, it is not impossible. Cryptographic systems use cryptographic algorithms to encrypt a message. These cryptographic algorithms use a key to encrypt or decrypt messages. In cryptography, this key is the important parameter that specifies the transformation of plaintext to ciphertext and vice versa. If you are able to guess or find the key used for decryption, then you can decrypt the messages and read them in clear text. 128-bit keys are common and considered strong. From a security perspective, to avoid guessing the key, cryptographic systems use randomly generated keys. This makes you devote considerable effort toward guessing the key. However, you still have a choice to determine the key used for encryption or decryption.

You can attempt to decrypt a message using all possible keys until you discover the key used for encryption. This method of discovering a key is called a brute-force attack. However, doing so requires a massive amount of processing power. It is a resource-intensive and time-intensive process. For any non-flawed protocol, the average time needed to find the key in a brute-force attack depends on the length of the key. If the key length is short, then it will take less time to find the key; if it is long, it will take more time. A brute-force attack will be successful if and only if the attacker has enough time to discover the key. However, the time required is relative to the length of the key.

The difficulty of a brute-force attack depends on various factors, such as

- The length of the key
- The number of possible values each component of the key can have
- The time it takes to attempt each key

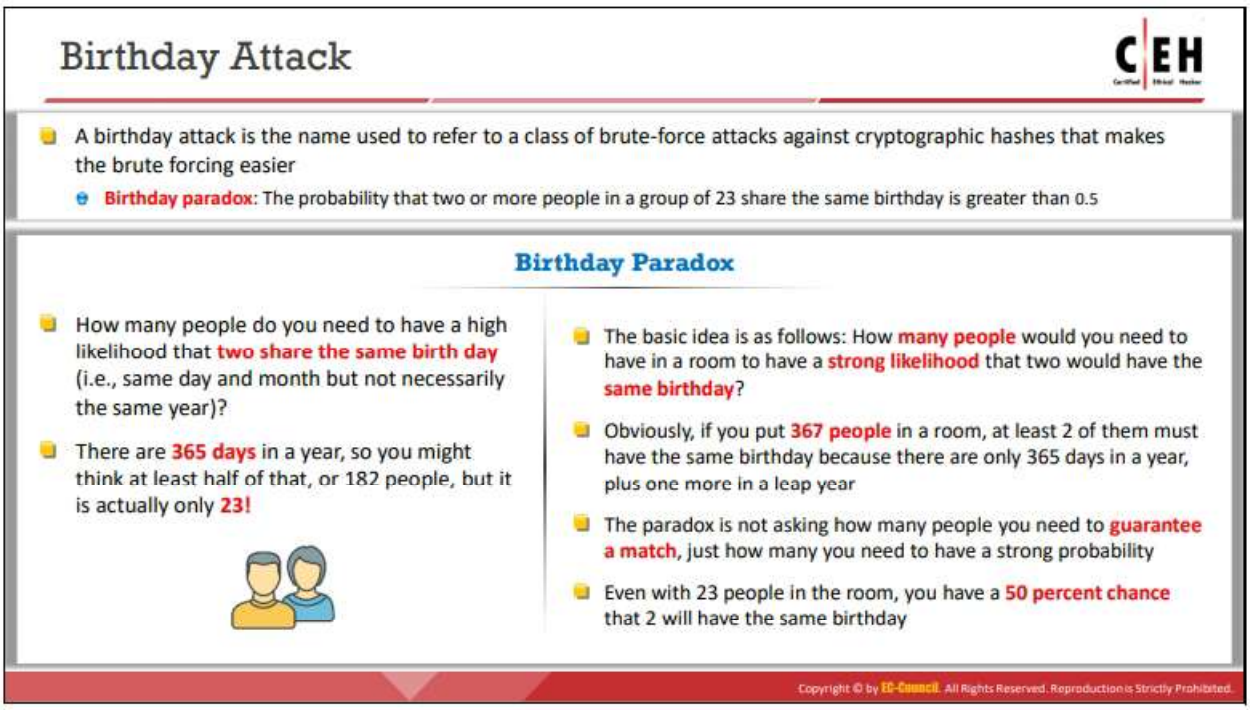
- If there is any mechanism that locks the attacker out after a certain number of failed attempts

For example, if a system could brute-force a DES 56-bit key in one second, then for an AES 128-bit key, it takes approximately 149 trillion years. To perform a brute-force attack, the attacker needs double the time for every additional bit of key length; the reason is that the number of keys doubles with an increase of one bit.

However, a brute-force attack is more likely to achieve results.

Power/Cost	40 bits (5 char)	56 bits (7 char)	64 bits (8 char)	128 bits (16 char)
$ 2K (1 PC. Can be achieved by an individual)	1.4 min	73 days	50 years	10^20 years
$ 100K (this can be achieved by a company)	2 sec	35 hours	1 year	10^19 years
$ 1M (Achieved by a huge organization or a state)	0.2 sec	3.5 hours	37 days	10^18 years

Table 20.5: Estimate time for a successful brute-force attack



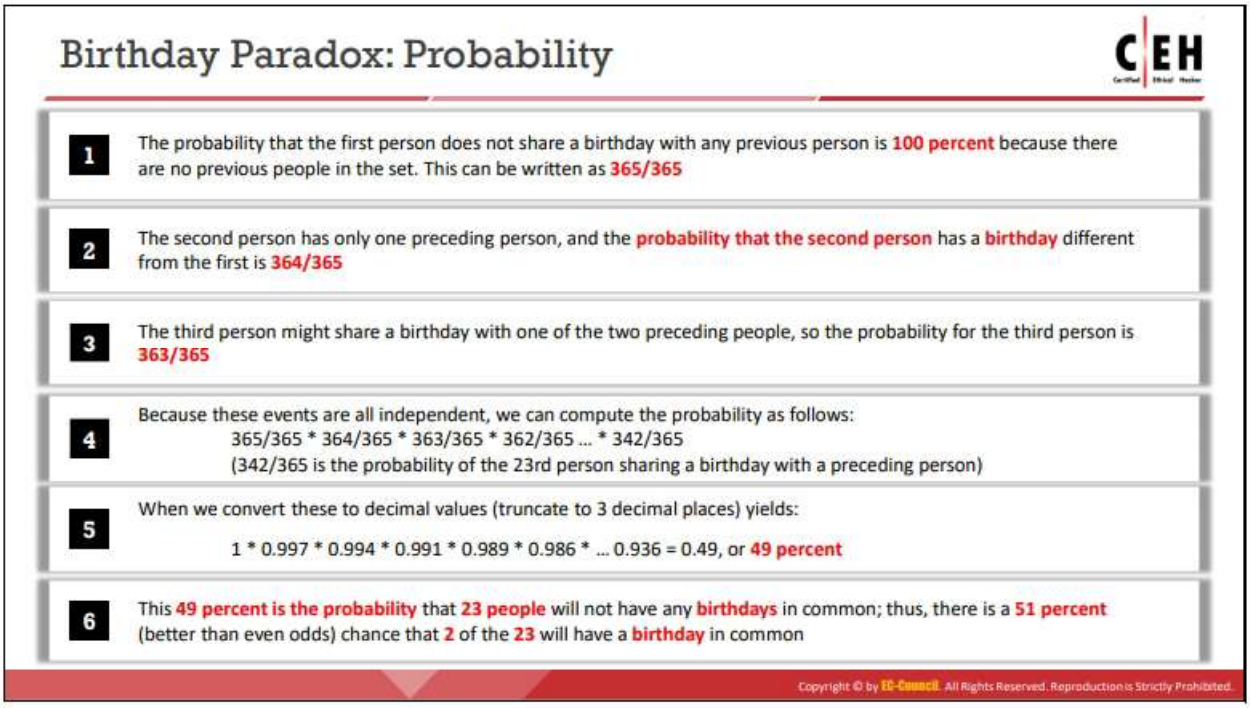
Birthday Attack

A birthday attack refers to a class of brute-force attacks against cryptographic hashes that renders brute-forcing easier to performs. This attack depends on the birthday paradox, which is the probability of two or more people in a group of 23 sharing the same birthday is greater than 0.5.

Birthday Paradox

For example, how many people are needed to have a high likelihood that two will share the same birthday (i.e., same day and month, not year). There are 365 days a year, and therefore, you might think that at least half or 182 people share the same birthday, when it is actually only 23!

The basic idea is as follows: How many people would you need to have in a room to have a strong likelihood that two amongst them would have the same birthday (same day and month, but not year). Obviously, if you put 367 people in a room, at least two of them must have their birthdays on the same day and month since there are only 365 days in a year, and an additional day in the case of a leap year. The paradox is not the number of people you need to guarantee a match, but the number of people you need to have a strong probability. Even with 23 people in a room, there is a 50% chance that two them will have their birthdays on the same day and month.

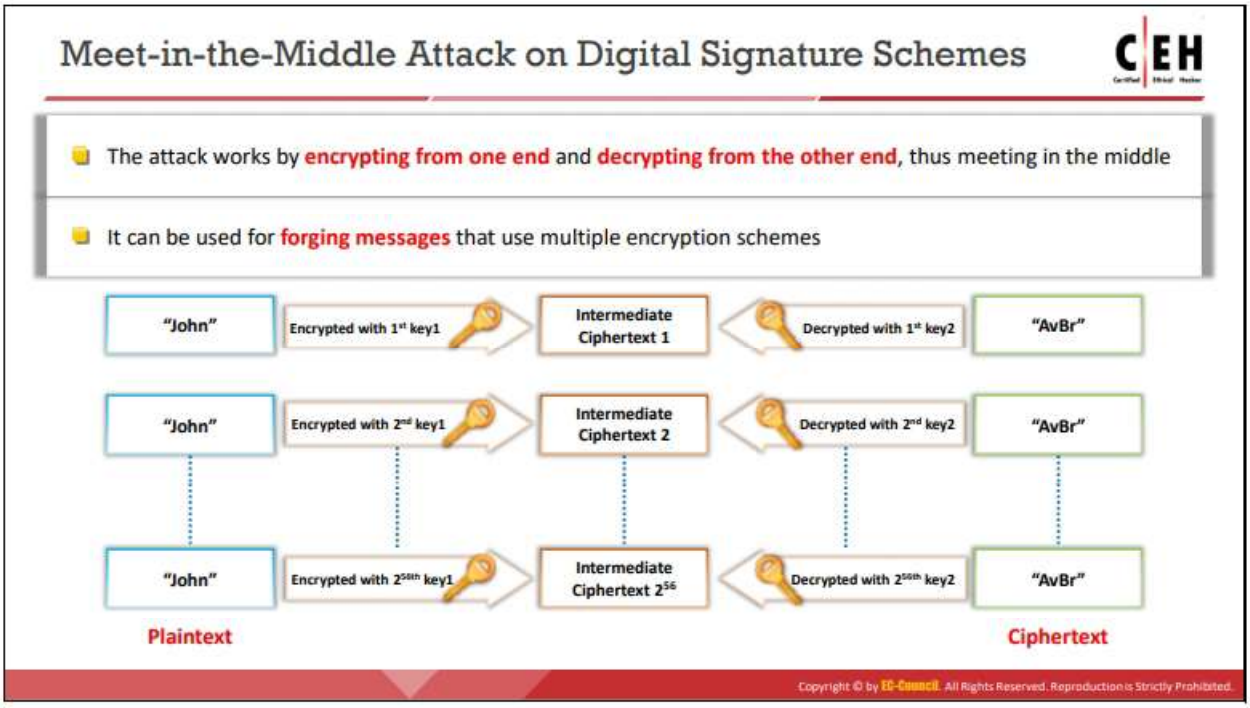


Birthday Paradox: Probability

The probability that the first person does not share a birthday with any previous person is 100% because there are no previous people in the set. This can be written as 365/365. The second person has only one preceding person, and the odds that the second person has a birthday different from the first are 364/365. The third person might share a birthday with two preceding people, so the odds of sharing a birthday with either of the two preceding people are 363/365. Because each of these are independent, we can compute the probability as follows: 365/365 * 364/365 * 363/365 * 362/365 … * 342/365 (342 is the probability of the 23rd person who shares a birthday with a preceding person). When we convert these to decimal values, it yields (truncating at the third decimal point) 1 * 0.997 * 0.994 * 0.991 * 0.989 * 0.986 * … 0.936 = 0.49 or 49%. This is the probability that 23 people will not have any birthdays in common; thus, there is a 51% (better than even odds) chance that two of the 23 will have a birthday in common.

The idea behind the birthday attack is to attempt to find a collision for a given hash. Now, assume that the hash is MD5 with a 128-bit output. You would have to try 2^128 possible hashes to guarantee a collision, which is a very large number. In decimal notation, it is 3.402823669209384634633746074317e+38

Now, from the birthday paradox, we need 1.174√2^128 or 21656477542535013597.184 hashes to guarantee a collision. Furthermore, this is still a very large number but many orders of magnitude smaller than the abovementioned value.



Meet-in-the-Middle Attack on Digital Signature Schemes

A meet-in-the-middle attack is the best attack method for cryptographic algorithms using multiple keys for encryption. This attack reduces the number of brute-force permutations required to decode text encrypted by more than one key. A meet-in-the-middle attack uses space-time trade-off; it is also a type of birthday attack because it exploits the mathematics behind the birthday paradox, and the attack consumes less time than an exhaustive attack. It is called a meet-in-the-middle attack because it works by encrypting from one end and decrypting from the other end, thereby meeting "in the middle."

In the meet-in-the-middle attack, the attacker uses a known plaintext message. The attacker has access to both the plaintext as well as the respective encrypted text. This attack is performed by attackers for forging messages that use multiple encryption schemes.

Consider an example where the plaintext is "**John**," and the resulting double-DES-encrypted message is "**AvBr.**" To recover both the keys (i.e., key1 and key2) used for encryption, the attacker performs a brute-force attack on key1 using all the **2^{56} different single DES** possible keys to encrypt the plaintext of "John" and saves each key and the resulting intermediate ciphertext in a table. The attacker brute-forces key2 and decrypts "AvBr" up to **2^{56} times**. The attack is successful when the second brute-force attack gives the same result as the intermediate ciphertext present in the ciphertext table after the first brute-force attack. Once the attacker finds a match, he/she can determine both keys and complete the attack. At most, this attack takes 2^{56} or a maximum of **2^{57} total operations**. This enables the attacker to gain access to the data easily compared with double DES.

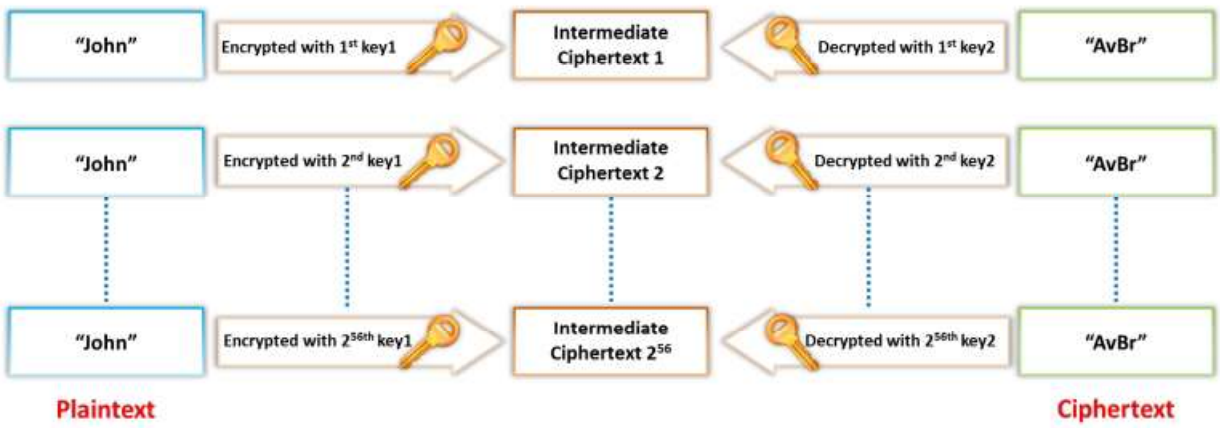
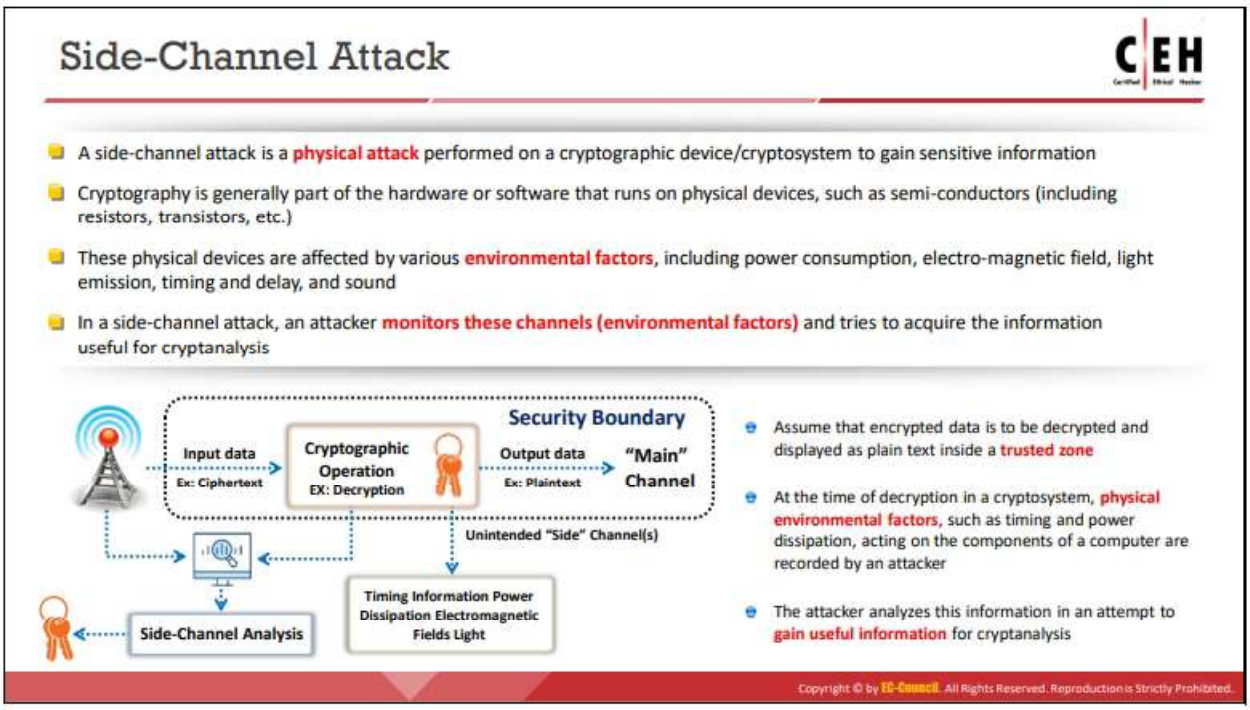


Figure 20.37: Meet-in-the-Middle attack on digital signature schemes



Side-Channel Attack

A side-channel attack is a physical attack performed on a cryptographic device/cryptosystem to gain sensitive information. Cryptography is generally part of the hardware or software that runs on physical devices such as semi-conductors (resistor, transistor, and so on) that interact with and affect various environmental factors as follows:

- **Power Consumption**

  Reveals operations that take place and parameters involved. It is applicable only to hardware cryptosystems. Power consumption analysis is of two types:

  - **Simple Power Analysis (SPA)**: Provides information regarding the instruction being executed at a certain time and the values of input and output
  - **Differential Power Analysis (DPA)**: It does not require the knowledge of the details of algorithm implementation; it exploits statistical methods

- **Electromagnetic Field**

  Computer components often generate electromagnetic radiation. By measuring the variations of the electromagnetic field over the chip surface, an attacker can predict its correlation to the underlying computation and data and may be able to deduce some valuable information about this computation and data.

- **Light Emission**

  Kuhn found that the average luminosity of a cathode ray tube (CRT) diffuse reflection of a wall is sufficient to reconstruct the signal displayed on the CRT. Thus, an attacker can gather ample information by reading the signals that a trusted computing platform's optical output channels emit.

According to Loughry and Umphress, one can deduce the data a computer is processing based on the optical radiation emitted from its LED (light-emitting diode) status indicators.

- **Timing and Delay**

  Systems often compute cryptographic algorithms without time consistency owing to performance optimizations. If such computations involves secret data, then the variations in time can be used to infer the secret information. Here, the attacker analyzes the time taken by a cryptographic device to process each message to discover the secret parameters.

- **Sound**

  Acoustic attacks exploit the sound produced during a computation. These acoustic emissions are from keyboards and computing components (e.g., CPU, memory)

In a side-channel attack, an attacker monitors these channels (environmental factors) and tries to acquire useful information for cryptanalysis. The information thus acquired is termed as side-channel information. Side-channel attacks are different from traditional/theoretical forms of attacks such as brute-force attacks. The side-channel attack depends on the way in which systems implement cryptographic algorithms rather than the algorithm itself.

Mitigation techniques for side-channel-attacks include the following:

- Use differential power analysis (DPA) proof protocols with delimited side-channel leakage characteristics and update the keys before the leakage accumulation is significant
- Use fixed-time algorithms (i.e., no data-dependent delays)
- Mask and blind algorithms using random nonces
- Implement differential matching techniques to minimize net data-dependent leakage from logic-level transitions
- Pre-charge registers and busses to remove leakage signatures from predictable data transitions
- Add amplitude or temporal noise to reduce the attacker's signal-to-noise ratio

Side-Channel Attack – Scenario

Assume that encrypted data are to be decrypted and displayed as plaintext inside a trusted zone. At the time of decryption in a cryptosystem, physical environmental factors, such as timing and power dissipation, acting on the components of a computer are recorded by an attacker. The attacker then analyzes this information to gain useful information for cryptanalysis.

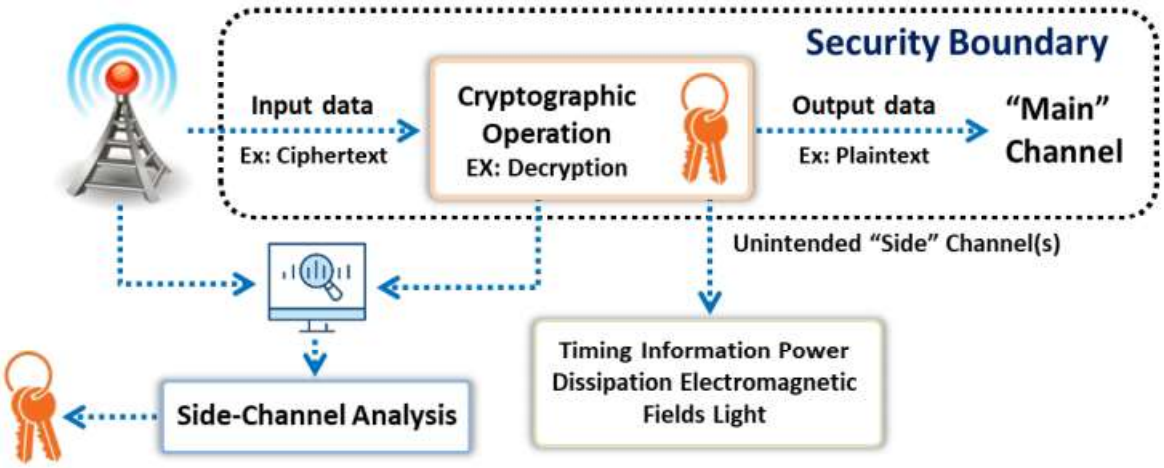
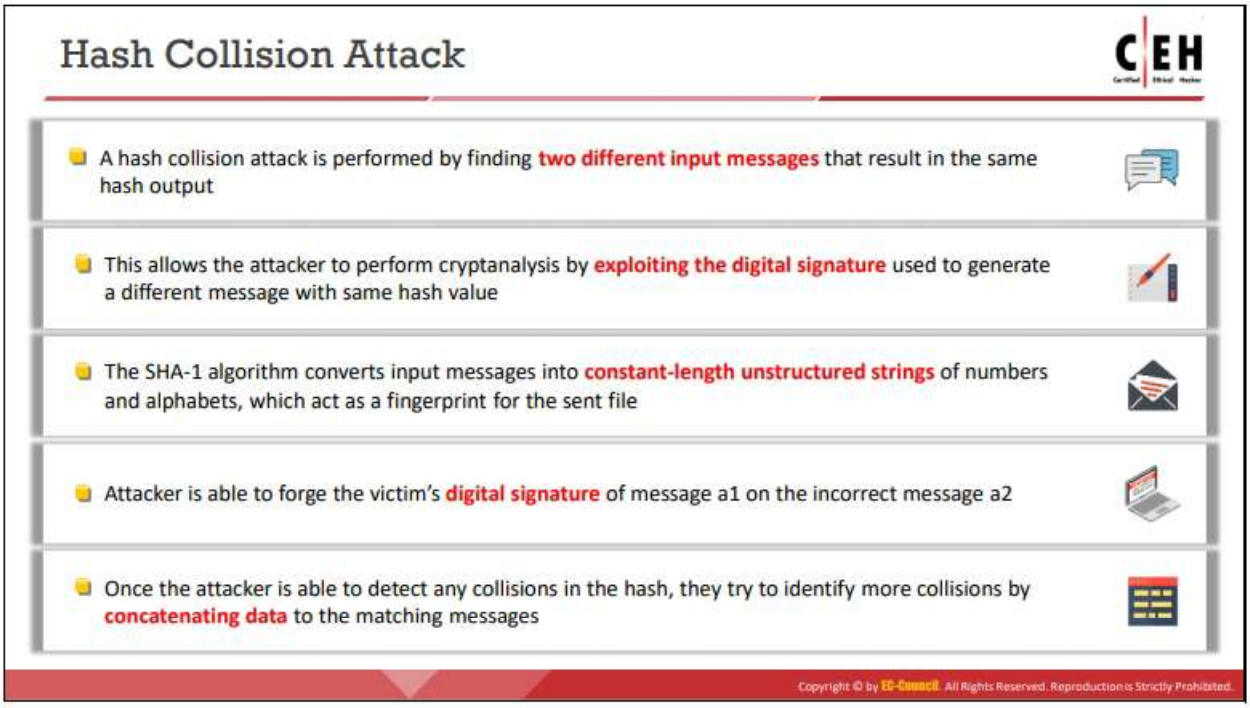


Figure 20.38: Side-Channel attack – scenario

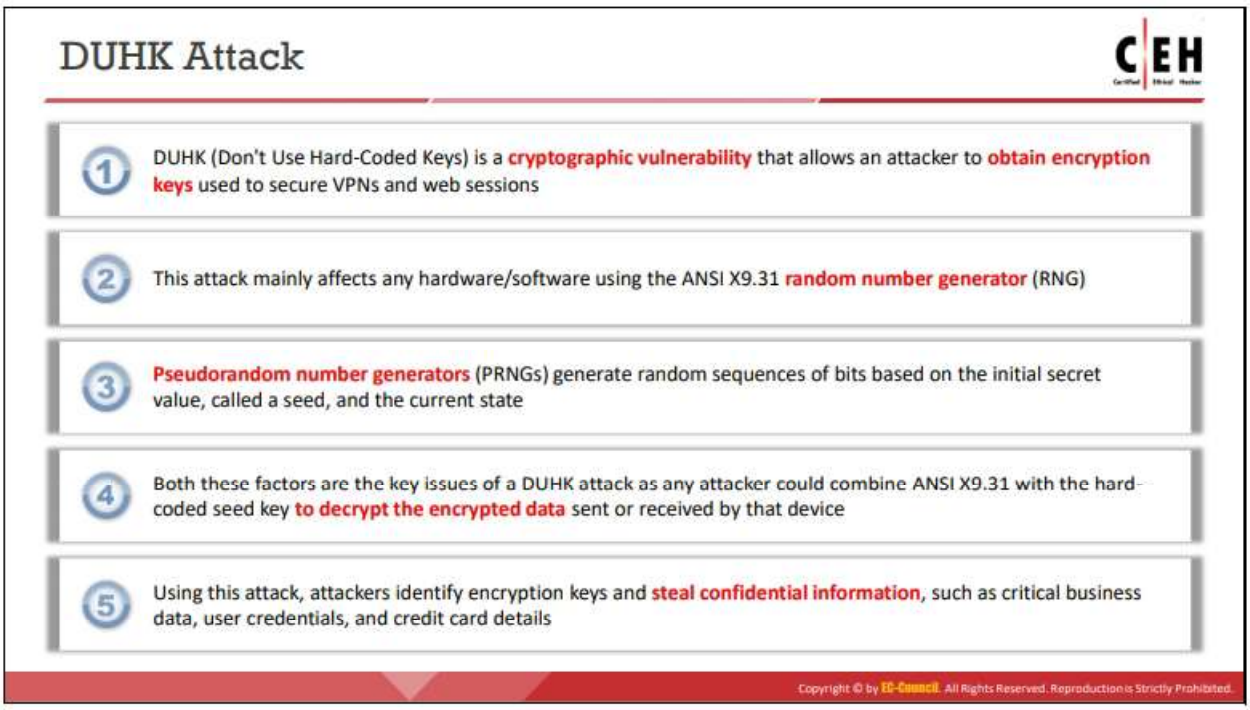


Hash Collision Attack

A hash collision attack is performed by finding two different input messages that result in the same hash output. For example, in a hash collision attack, "**hash(a1) = hash(a2)",** where a1 and a2 represent some random messages. Since the algorithm itself randomly selects these messages, attackers have no role in the content of these messages. This allows the attacker to perform cryptanalysis by exploiting the digital signature used to generate a different message with the same hash value.

One of the most popular hash functions is SHA-1, which is widely used as a digital signature algorithm. SHA-1 converts an input message into a constant length of unstructured strings of numbers and alphabets, which act as a fingerprint for the sent file. Therefore, the attacker tries to identify similar hashed output to get the digital signatures of the victim. This allows the attacker to forge the victim's digital signature of message a1 on message a2.

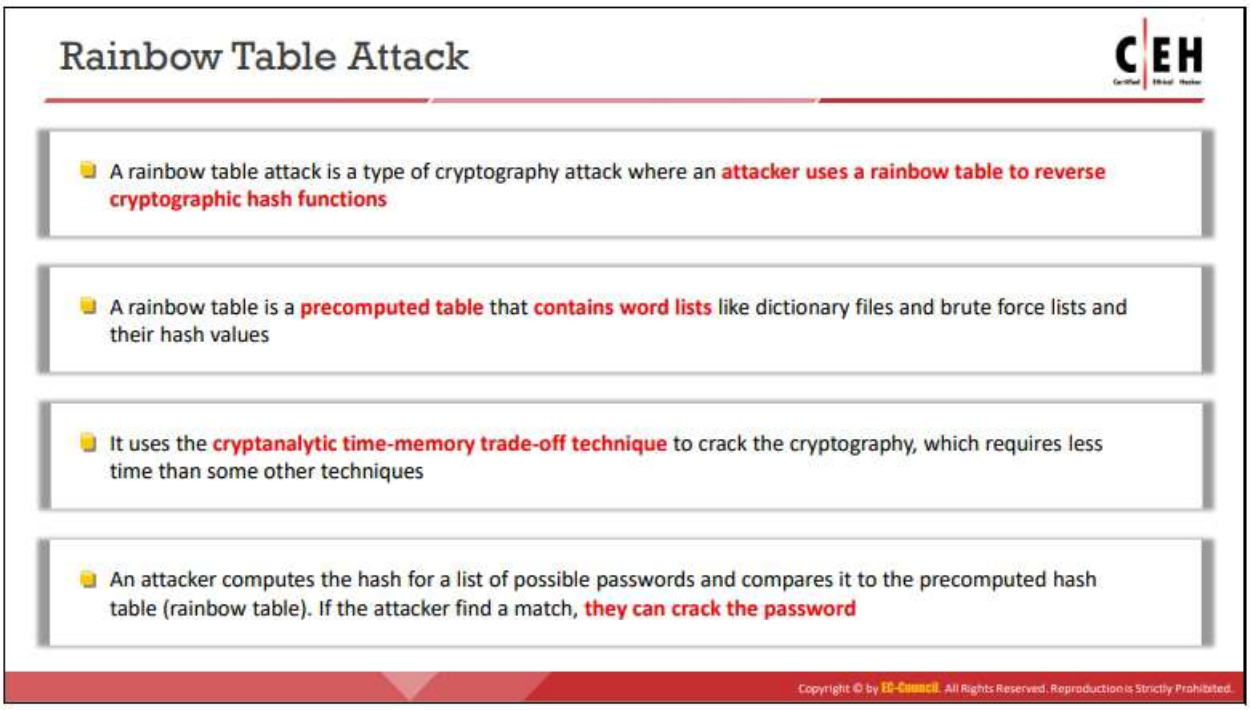
Once the attacker detects a collision in the hash, he/she can identify more collisions by concatenating the data to matching messages.



DUHK Attack

Don't Use Hard-Coded Keys (DUHK) is a cryptographic vulnerability that allows attackers to obtain encryption keys used to secure VPNs and web sessions. This attack mainly affects any hardware/software using the ANSI X9.31 Random Number Generator (RNG). Pseudorandom number generators (PRNGs) generate random sequences of bits based on the initial secret value, called seed, and the current state. The PRNG algorithm generates cryptographic keys that are used to establish a secure communication channel over the VPN. In some cases, the seed key is hardcoded into the implementation. Both the factors are key issues of the DUHK attack, as any attacker can combine ANSI X9.31 with the hard-coded seed key to decrypt the encrypted data sent or received by that device.

Man-in-the-middle attackers use the DUHK attack to learn the seed value, observe the current session, and obtain the current state value. Using this attack, attackers can identify encryption keys and steal confidential information such as critical business data, user credentials, and credit card details.

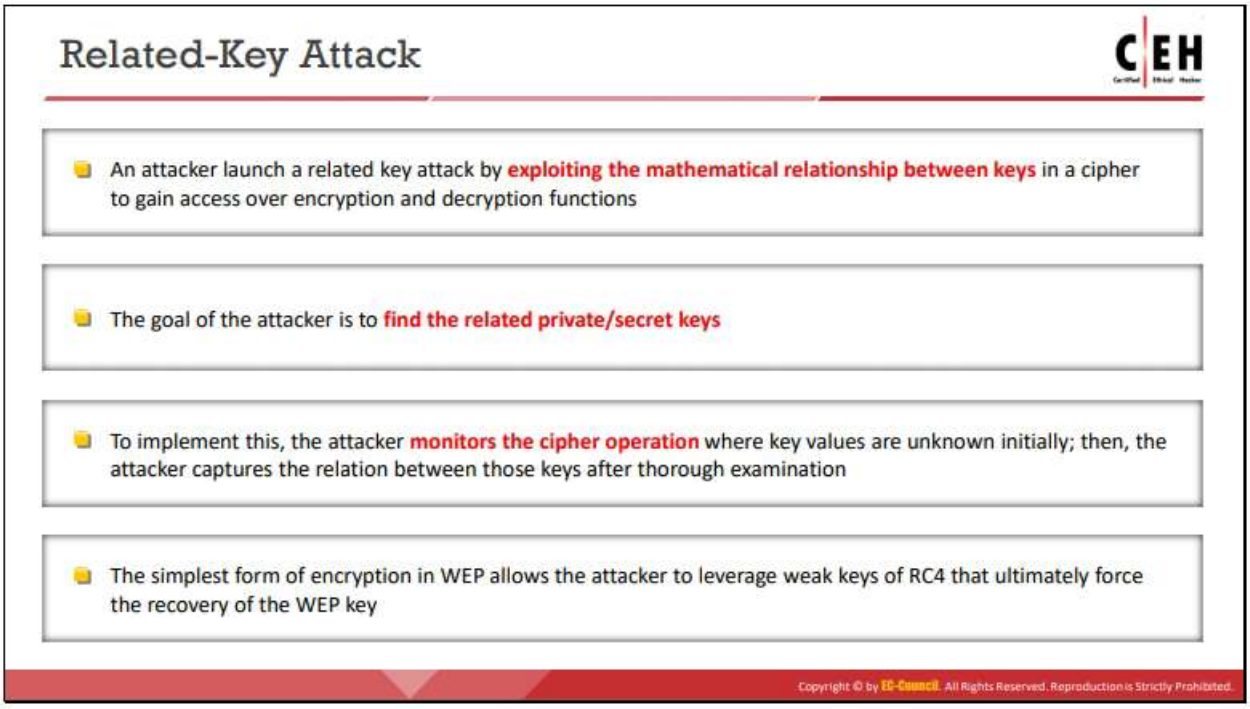


Rainbow Table Attack

A rainbow table attack is a type of cryptography attack whereby an attacker uses a rainbow table for reversing cryptographic hash functions. A rainbow table attack uses the cryptanalytic time-memory trade-off technique, which is less time consuming than other techniques. It uses already calculated information stored in memory for encryption. In the rainbow table attack, the attacker creates a table of all the possible passwords and their respective hash values, called a rainbow table, in advance.

A rainbow table contains word lists such as dictionary files and brute-force lists and their hash values. It is a lookup table particularly used for recovering a plaintext password from a ciphertext. The attacker uses this table to look for the password and tries to recover it from password hashes.

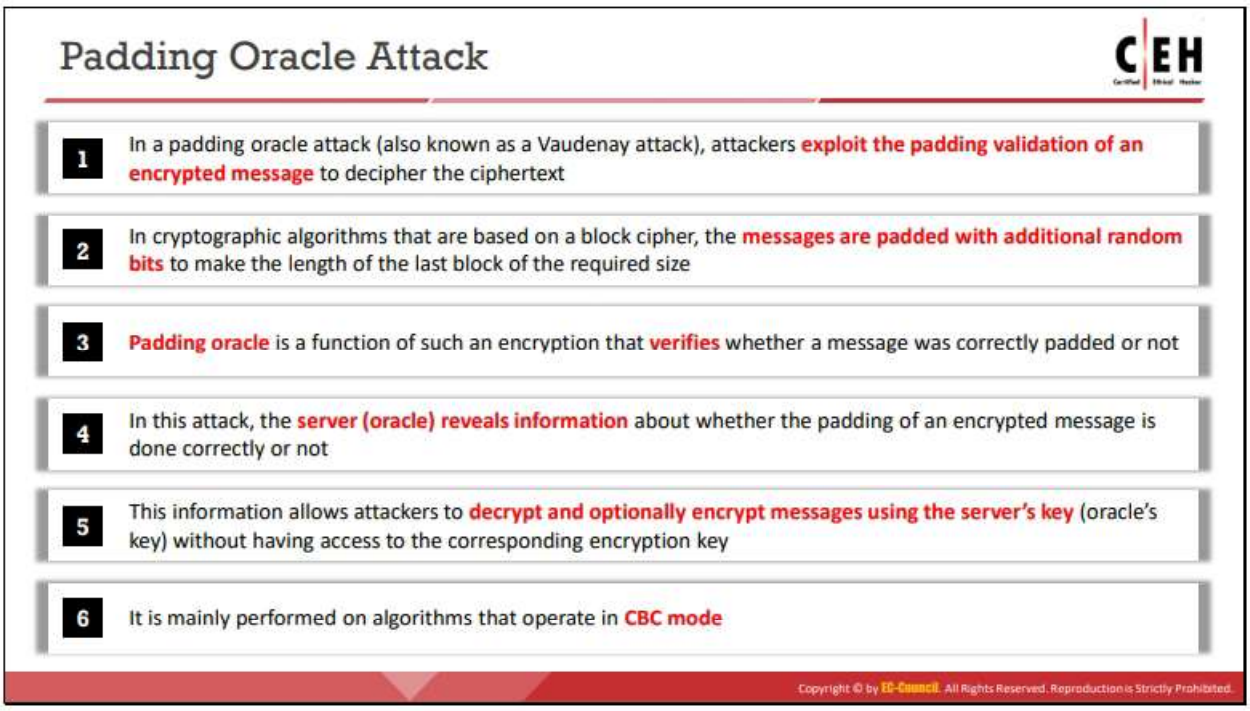
An attacker computes the hash for a list of possible passwords and compares it with the pre-computed hash table (rainbow table). If a match is found, then he/she can crack the password. It is easy to recover passwords by comparing the captured password hashes with pre-computed tables.



Related-Key Attack

Attackers launch a related-key attack by exploiting the mathematical relationship between the keys in a cipher and gain access to encryption and decryption functions. The attacker's motive for launching this attack is to find the related private/secret keys. To implement this attack, the attacker monitors the cipher operation where key values are initially unknown; then, the attacker captures the relation between those keys after a thorough examination. For instance, the attacker observes and finds that the last 80 bits of the keys are same at all times, but he/she does not initially know about these bits.

The failure in the WEP cryptogram, i.e., when used in wireless networks, is the best example of this attack. In this attack, each AP and user interface device uses the same key. The encryption used in WEP is a stream cipher known as RC4; it is important to note that the same keys should not be repeated in the stream cipher. To avoid this, WEP integrates a 24-bit initial vector (IV) in every packet transferred. The RC4 key for that particular packet is the IV associated with the WEP key. WEP keys need to be changed manually, however, this is rarely done. Hence, the attacker notices that the keys used for encryption are often the same. This drawback poses various risks on WEP, especially using the birthday paradox, because for every 4096 packets, two parties will share the same IV and hence the same RC4 key. This simple form of encryption allows the attacker to leverage weak RC4 keys, which ultimately forces the recovery of the WEP key.

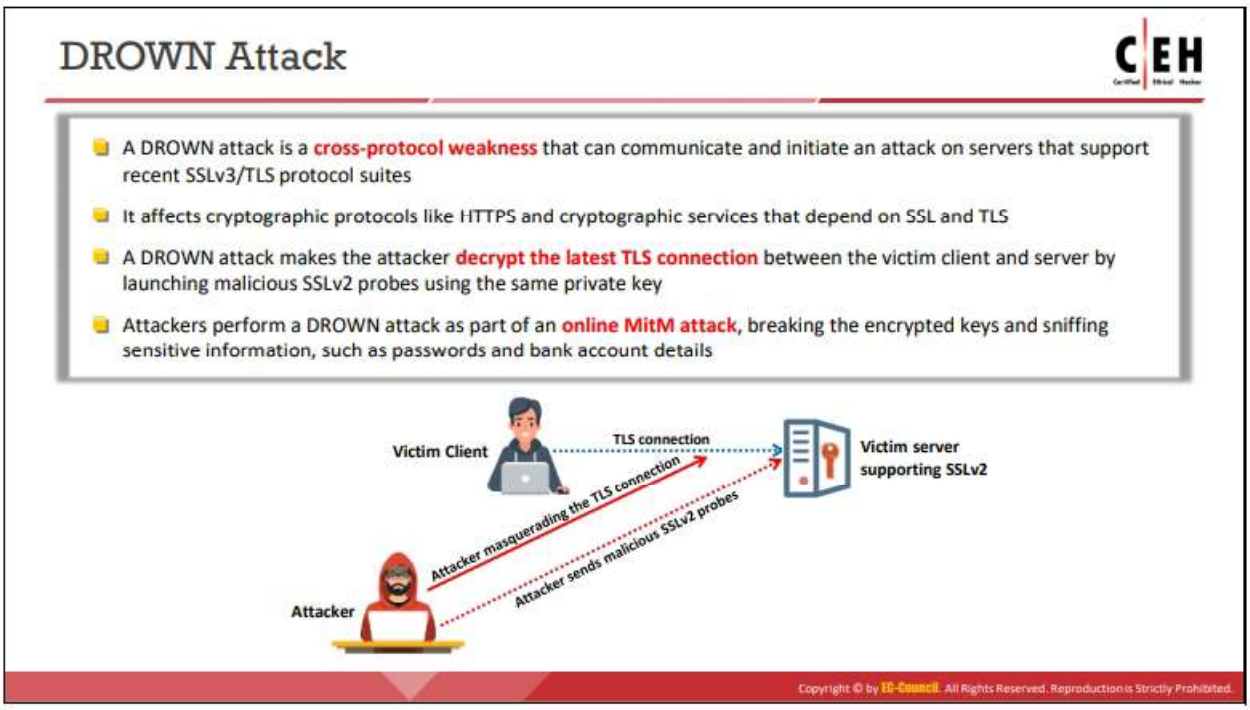


Padding Oracle Attack

In a padding oracle attack, the attackers exploit the padding validation of an encrypted message to decipher the ciphertext. Such an attack is also known as a Vaudenay attack. In many cryptographic algorithms based on a block cipher, the messages are padded with additional random bits so that the length of the last block is of the required size. Padding oracle is a function of such encryption that verifies if a message was correctly padded. This attack is mainly performed on algorithms that operate in the CBC (Cipher Block Chaining) mode.

In this attack, the server (oracle) reveals information about whether the padding of an encrypted message was correctly done. In some cases, this information allows attackers to decrypt and optionally encrypt messages using the server's key (oracle's key) without having access to the corresponding encryption key.

For example, consider a scenario with a standard implementation of CBC decryption. The server decrypts all the ciphertext blocks, verifies the padding, removes all the additional padding done during the encryption process, and then returns the original message to application or user. If, for example, the server is unable to decrypt the message due to a padding error and returns an error message "Decryption failure: Invalid Padding" instead of a generic message "Decryption failed", this information can be exploited by an attacker. The attacker can use the server as a padding oracle to decipher the encrypted messages.



DROWN Attack

Decrypting RSA with Obsolete and Weakened eNcryption (DROWN) is a grave vulnerability that can affect important cryptographic protocols such as HTTPS and other cryptographic services that depend on SSL and TSL. The DROWN attack is a cross-protocol weakness that can communicate and initiate an attack on servers supporting recent SSLv3/TLS protocol suites. It is a new form of cross-protocol Bleichenbacher padding oracle attack.

The server is critically vulnerable to the DROWN attack if

- The server permits SSLv2 connection, which is mostly caused by a misconfiguration or incorrect default settings.
- The same private key certificate is used on a different server that allows SSLv2 connection, and it also makes the TLS server vulnerable, as the SSLv2 server can leak the key information.

The DROWN attack allows the attacker to decrypt the latest TLS connection between the victim client and the server by launching malicious SSLv2 probes using the same private key. Using this attack, the attacker can also force the victim client and server to use the RSA key exchange. Thus, the attacker can disrupt connections among the latest browsers and servers that favor the use of latest techniques, i.e., perfect-forward-secret key exchange, such as DHE and ECDH.

Attackers perform the DROWN attack as part of an online man-in-the-middle (MITM) attack, breaking encrypted keys, sniffing or stealing sensitive information such as passwords and bank account details, and accessing personal emails or messages. By performing this attack, the attacker can also masquerade as a secure website and thus seize or change the website contents.

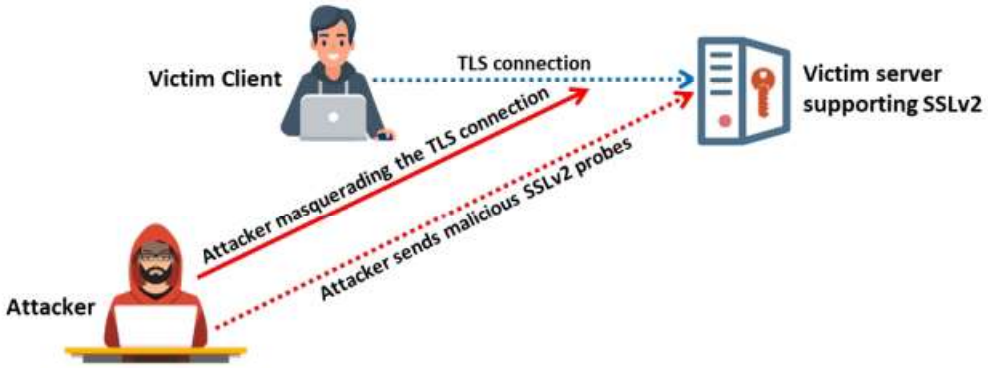
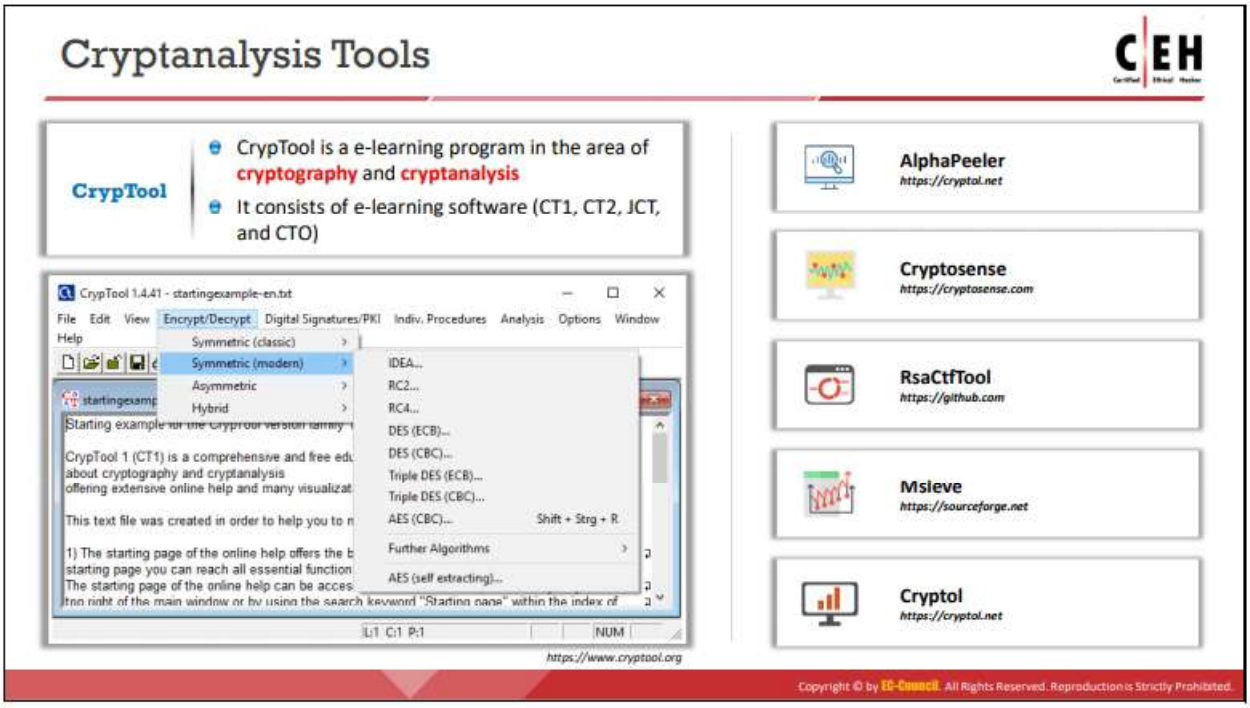


Figure 20.39: DROWN attack



Cryptanalysis Tools

Attackers use cryptanalysis tools to analyze and break ciphers. Some cryptanalysis tools are discussed as follows.

- **CrypTool**

  Source: *https://www.cryptool.org*

  The CrypTool project develops e-learning programs in the area of cryptography and cryptanalysis. It consists of e-learning software (CT1, CT2, JCT, and CTO).

  CrypTool 1 (CT1) – It is written in C++ and is a Windows program. It supports classical and modern cryptographic algorithms (encryption and decryption, key generation, secure passwords, authentication, secure protocols, etc.). It is used to perform cryptanalysis of several algorithms (Vigenère, RSA, AES, etc.)

  CrypTool 2 (CT2) – It supports visual programming GUI and execution of cascades of cryptographic procedures. It runs under Windows**.**

  JCrypTool (JCT) – It allows comprehensive cryptographic experimentation on Linux, MAC OS X, and Windows. It also allows users to develop and extend its platform in various ways with their own crypto plug-ins.

  CrypTool-Online (CTO) – It runs in a browser and provides a variety of encryption methods and analysis tools.

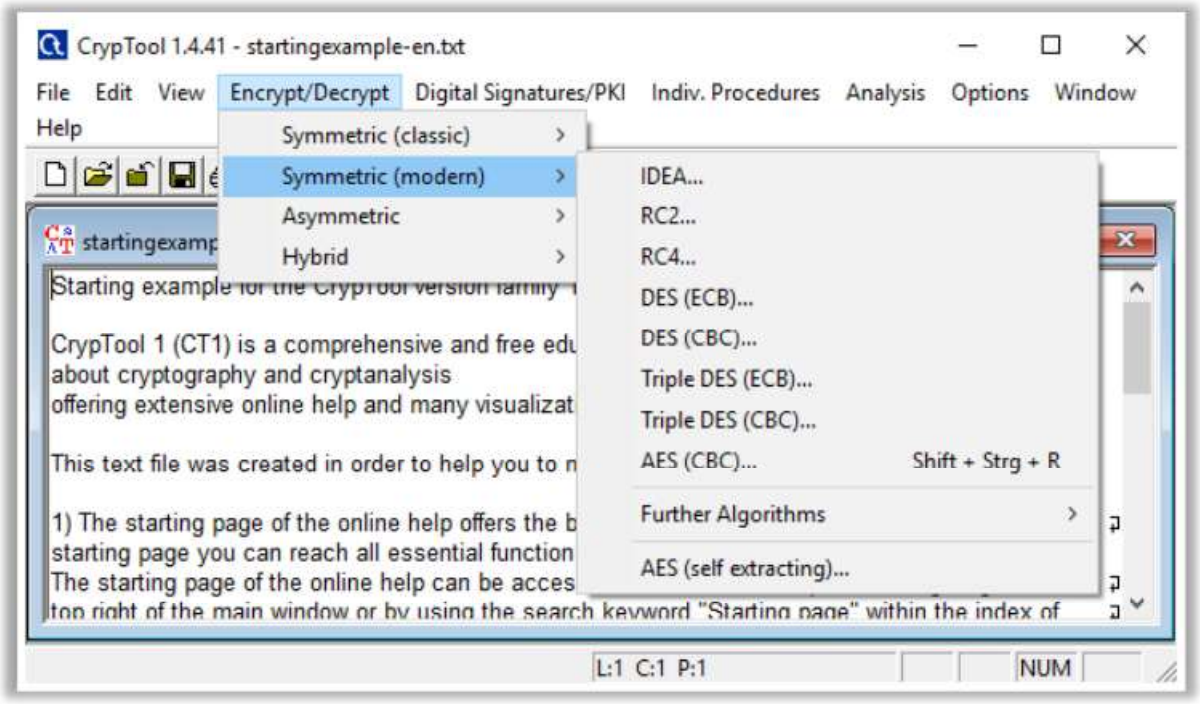


Figure 20.40: Screenshot of CrypTool

Some additional cryptanalysis tools are as follows:

- Cryptosense (*https://cryptosense.com*)
- RsaCtfTool (*https://github.com*)
- Msieve (*https://sourceforge.net*)
- Cryptol (*https://cryptol.net*)
- CryptoBench (*http://www.addario.org*)

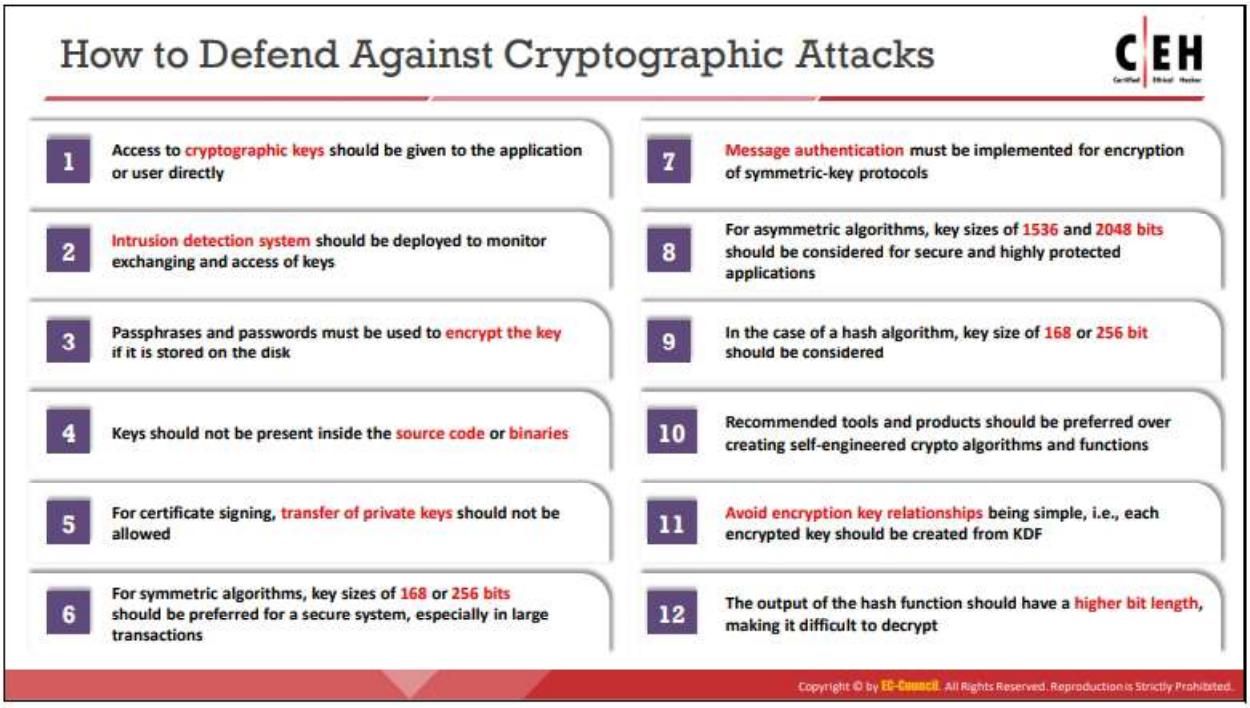
Online MD5 Decryption Tools

Some online MD5 decryption tools that can be used to decrypt the MD5 hash value to discover the original message are as follows:

- MD5 Decoder (*https://www.dcode.fr*)
- CrackStation (*https://crackstation.net*)
- Md5() Encrypt & Decrypt (*https://md5decrypt.net*)
- md5hashing (*https://md5hashing.net*)
- MD5 Decrypt (*http://www.md5decrypt.org*)
- MD5 Decryption (*https://www.md5online.org*)
- MD5Decrypter (*https://www.md5decrypter.com*)
- OnlineHashCrack.com (*https://www.onlinehashcrack.com*)
- HashKiller.co.uk (*https://hashkiller.co.uk*)
- Md5.My-Addr.com (*http://md5.my-addr.com*)
- cmd5.org (*https://www.cmd5.org*)
- md5this (*http://www.md5this.com*)
- Decode MD5 Hash (*https://md5.web-max.ca*)
- md5 decoder tool (*http://md5.my-addr.com*)

Countermeasures

Attackers use various cryptanalysis methods and techniques to break cryptosystems and steal confidential information that is transmitted in the network. This section discusses some countermeasures that can be adopted to prevent such attacks.

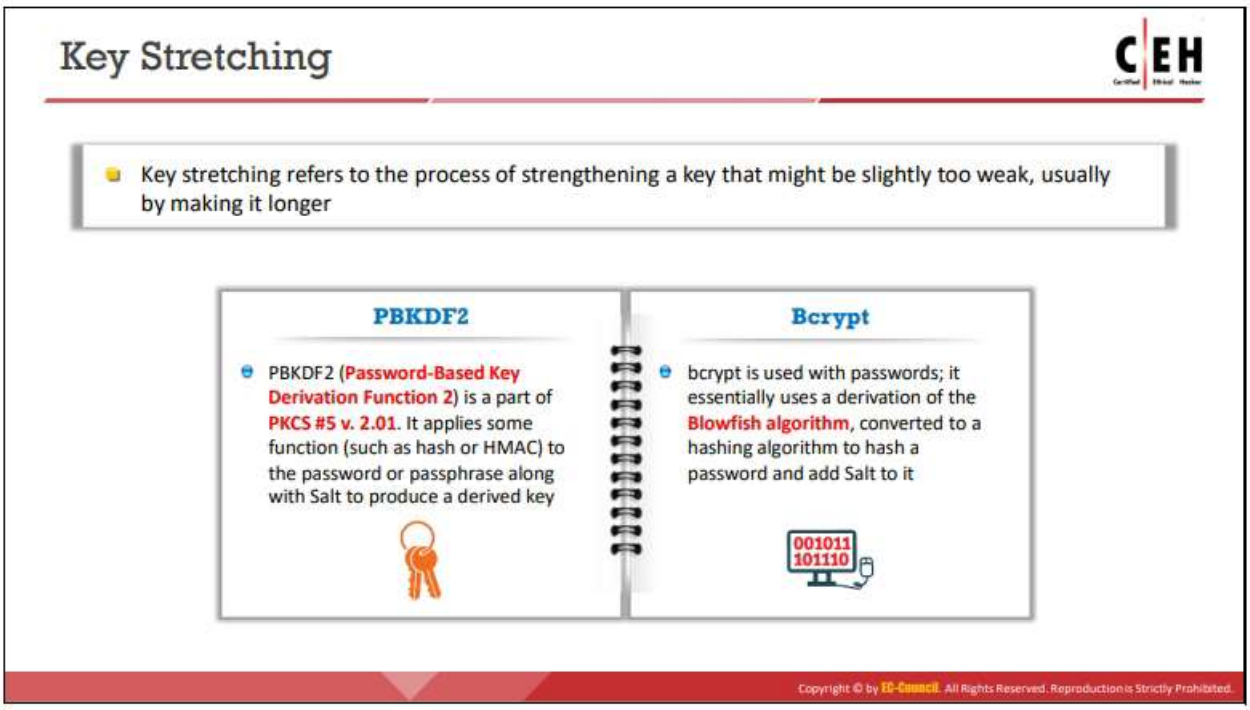


How to Defend Against Cryptographic Attacks

The following countermeasures can be adopted to prevent cryptographic attacks:

- Access of cryptographic keys should be given directly to the application or user.
- IDS should be deployed to monitor exchanging and access of keys.
- Passphrases and passwords must be used to encrypt the key, if stored in the disk.
- Keys should not be present inside the source code or binaries.
- For certificate signing, the transfer of private keys should not be allowed.
- For symmetric algorithms, a key size of 168 bits or 256 bits should be preferred for a secure system, especially in the case of large transactions.
- Message authentication must be implemented for the encryption of symmetric-key protocols.
- For asymmetric algorithms, a key size of 1536 bits or 2048 bits should be considered for secure and highly protected applications.
- In the case of hash algorithms, a key size of 168 or 256 bits should be considered.
- Only recommended tools or products should be used rather than self-engineered crypto algorithms or functions.
- Impose a limit on the number of operations per key.
- The output of the hash function should have a larger bit length that makes it difficult to decrypt.

- Design applications and protocols that can avoid simple encryption key relationships, i.e., each encrypted key should be created from a key derivation function (KDF).
- Upgrade to the latest security standards.
- Use strong key schedules to mitigate the risks of related key attacks.



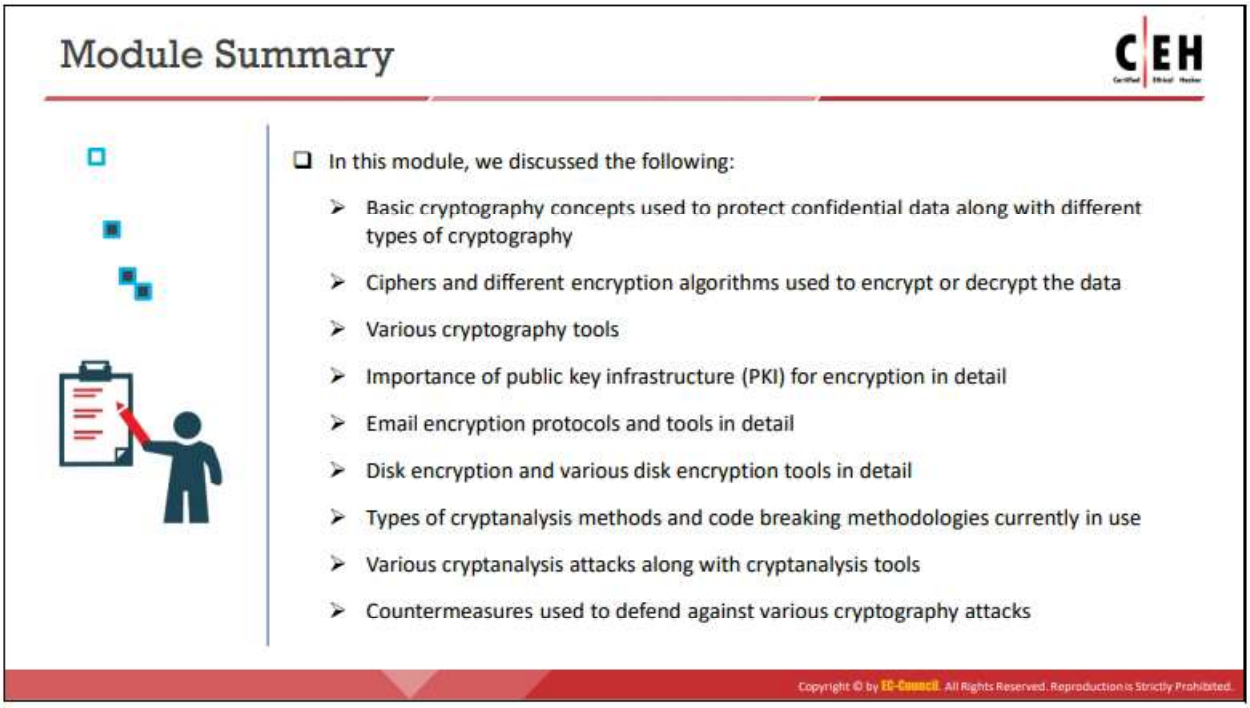
Key Stretching

Key stretching refers to processes used to make a weak key stronger, usually by making it longer. This technique helps in defending against brute-force attacks. In general, passwords or passphrases generated by end users are weak and predictable. Hence, key stretching helps security professionals/users to prevent such attacks by strengthening their passwords.

In the key stretching technique, the initial key is given as input to an algorithm that generates an enhanced key. The key must be sufficiently resistant to brute-force attacks. It is very difficult for the attackers to predict the enhanced key as they need to try every possible combination of the key or likely combinations of the enhanced key.

There are many functions and libraries that perform key stretching as part of their working:

- Password-Based Key Derivation Function 2 (PBKDF2) is part of PKCS #5 v. 2.01. It applies some function (such as a hash or HMAC) to the password or passphrase along with Salt to produce a derived key.
- bcrypt is used with passwords, and it essentially uses a variant of the Blowfish algorithm, converted to a hashing algorithm, to hash a password and add Salt to it.



Module Summary

This module discussed basic cryptography concepts used to protect confidential data as well as different types of cryptography. It also described ciphers and different encryption algorithms used to encrypt or decrypt data in detail. Furthermore, it illustrated various cryptography tools. It then highlighted the importance of PKI in encryption and discussed the email encryption protocols and tools in detail. It also discussed disk encryption along with various disk encryption tools. Moreover, it explained the various types of cryptanalysis methods and code breaking methodologies in use. Subsequently, it presented the various types of cryptanalysis attacks and cryptanalysis tools. Finally, it ended with an explanation of the countermeasures against various cryptography attacks.