Module 19
Cryptography

Ansh Bhawnani

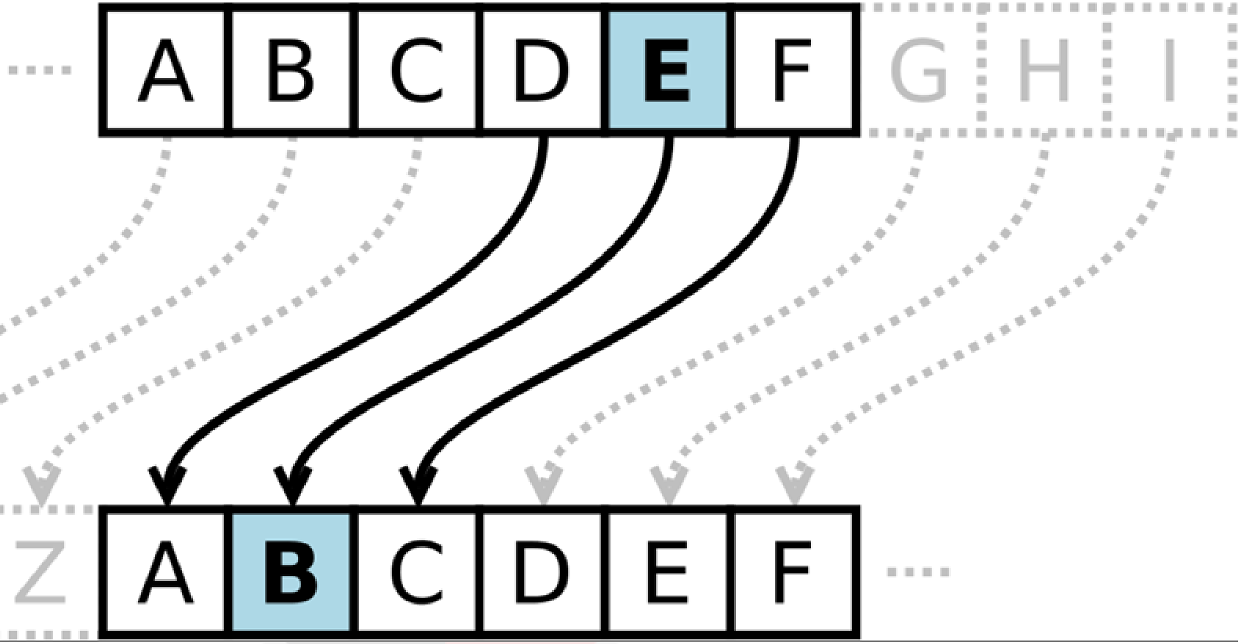
Cryptography concepts

Module 19

Cryptography concepts

- Study of techniques for secure communications through insecure channels
- *Encryption* is the transformation of data into a form in which it cannot be made sense of without the use of some key.
- Modern cryptography exists at the intersection of the disciplines of mathematics, computer science, electrical engineering, communication science, and physics.
- **Teaches how to convert sensible data into random junk!**

Cryptography concepts



Cryptography concepts

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

Cryptography concepts

Cryptographic Terms

Plaintext:

- Original message
- Anyone can read
- E.g, “Alice”

Cipher

- Cryptographic algorithm or function
- Tells how to transform plaintext into that random junk

Cryptography concepts

Cryptographic Terms

Cipher Key

- string of characters
- Cipherfunction(plaintext + cipher key) = ciphertext

Cipher text

- That random junk we got after applying cipher key on plaintext
- Unreadable, useless
- E.g., “#r4Tf2%#”

Cryptography concepts

Cryptographic Terms

Encryption

- Converting plaintext into ciphertext using cipher key.
- Cannot be reversed without the use of the key

Decryption

- Converting ciphertext into plaintext using cipher key.
- Cannot be reversed without the use of the key

Cryptography concepts

Cryptographic Terms

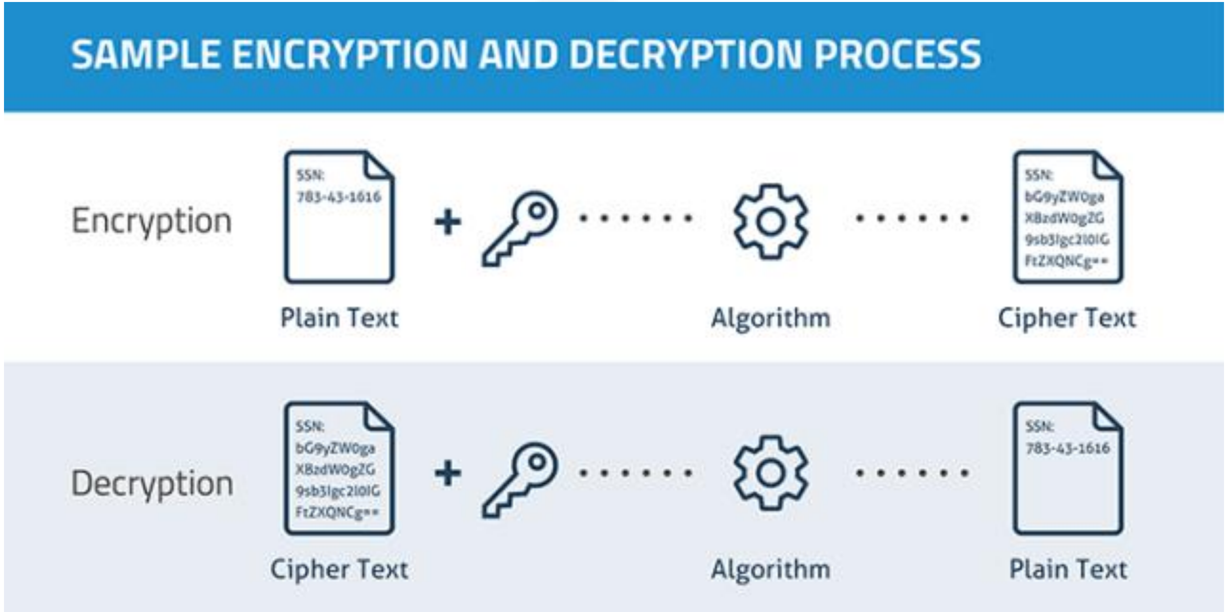
Hash

- Random fixed length string
- Irreversible one way function
- Provides integrity
- E.g., **MD5**, **SHA-1**

Salt

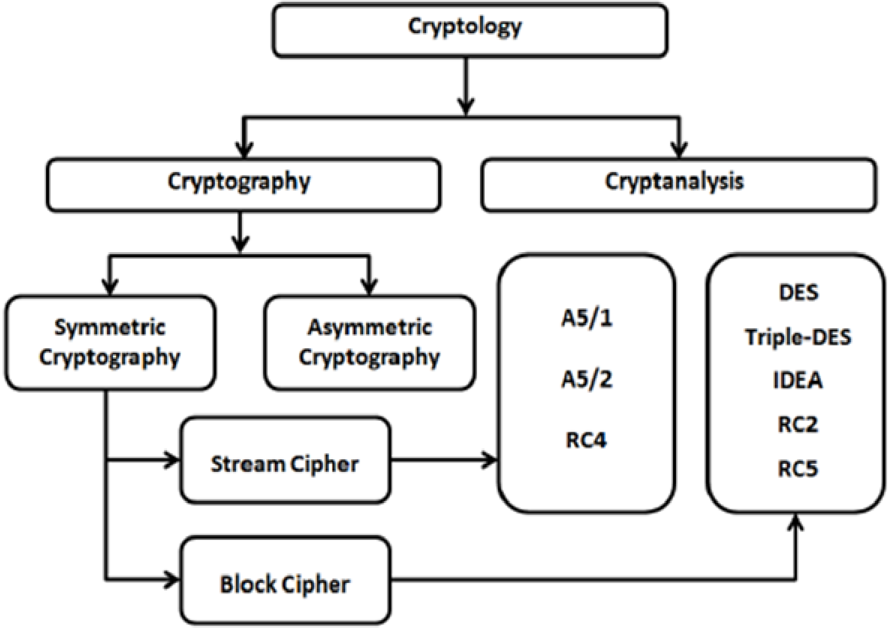
- Additional security
- Eradicates brute force and cracking
- Random string Appended at beginning or end of plaintext

Cryptography concepts



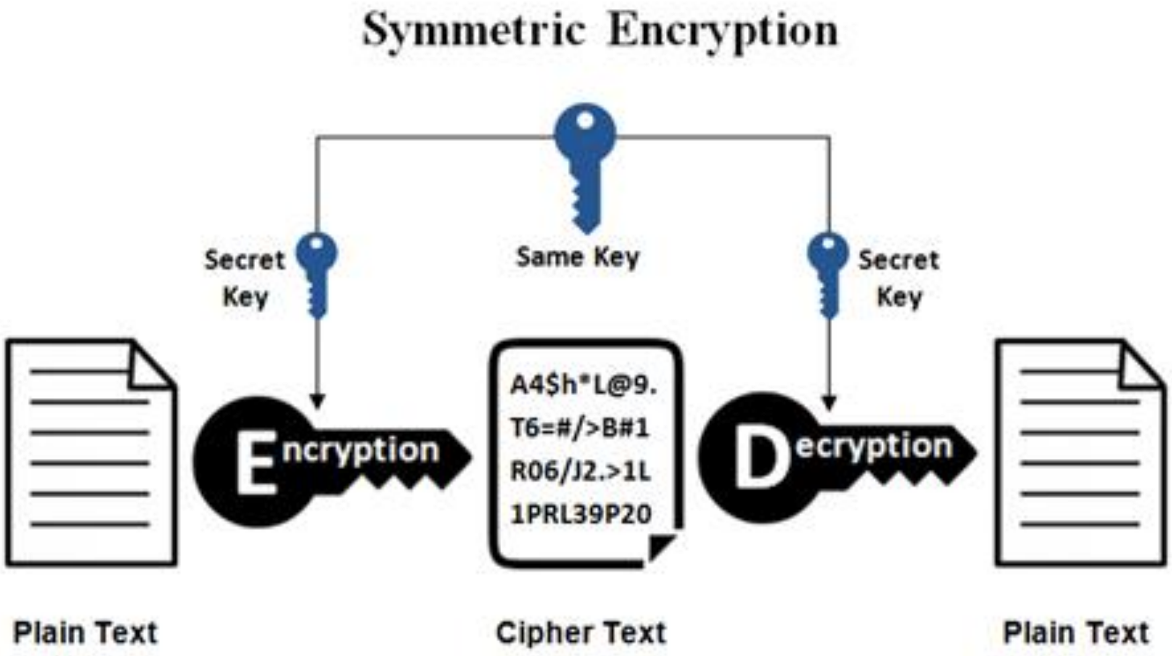
Cryptography concepts

Types of Cryptography



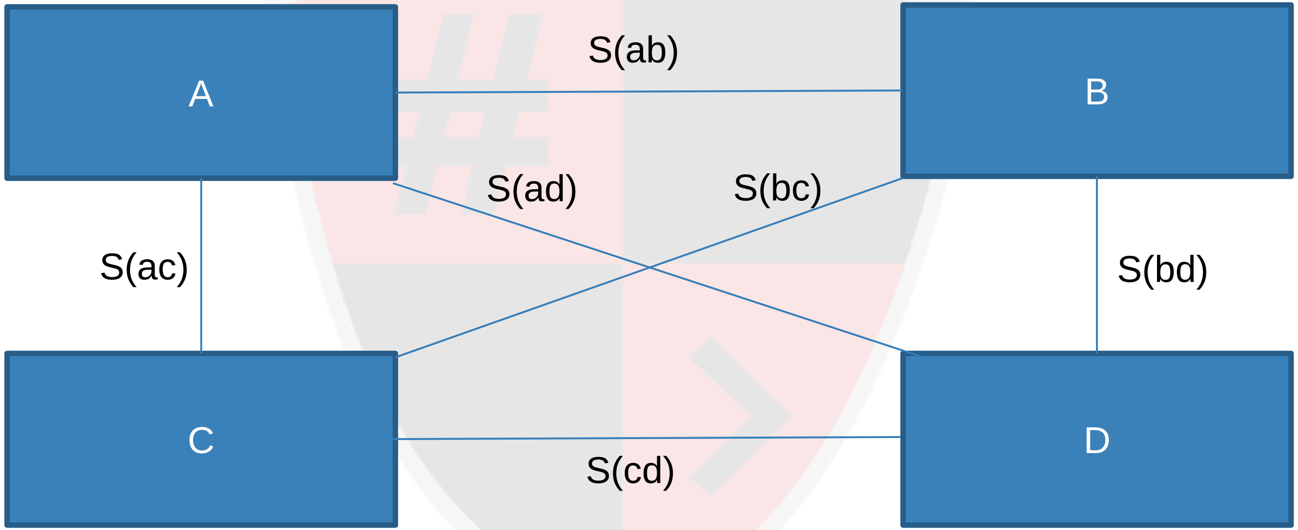
Cryptography concepts

Symmetric or Secret Key Cryptography



Cryptography concepts

Symmetric or Secret Key Cryptography

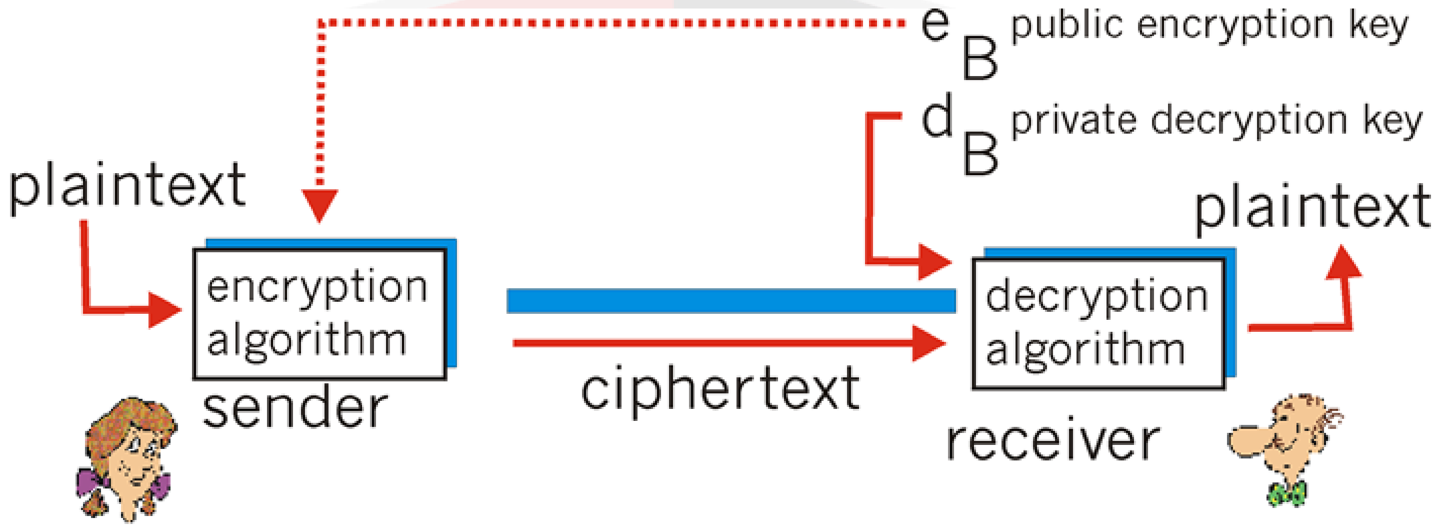


Cryptography concepts

- **Advantages**
  - Extremely Secure
  - Relatively Fast
- **Disadvantages**
  - Key management
  - Key distribution
  - Large number of keys needed (O(n^2))

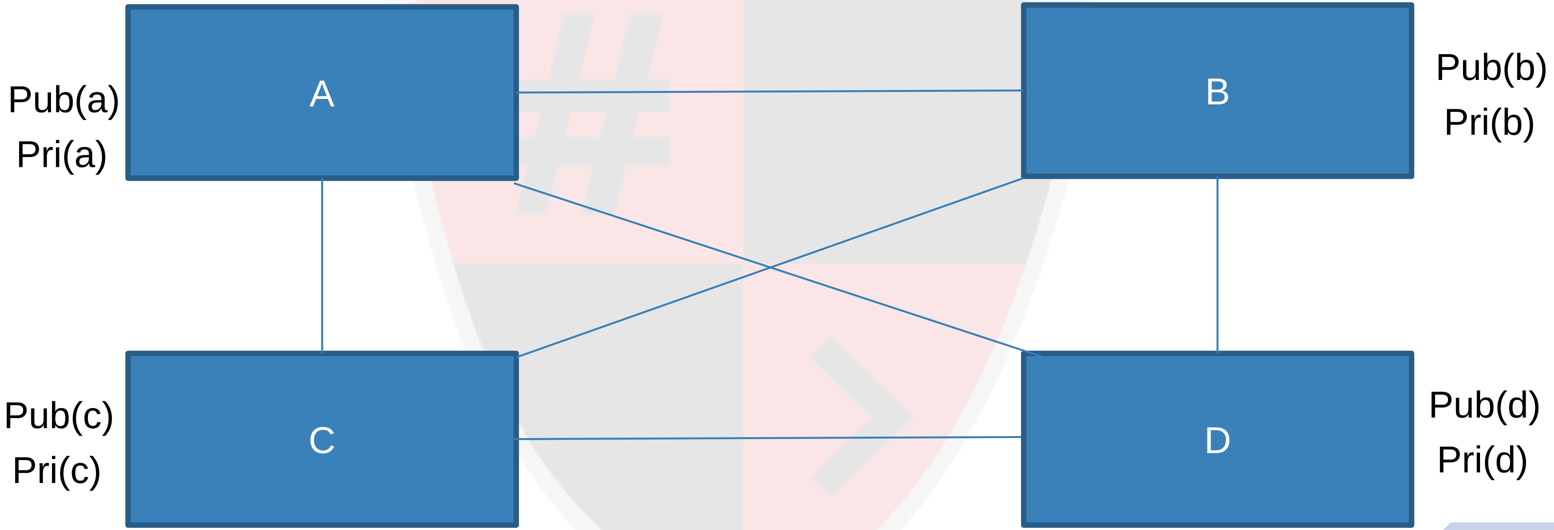
Cryptography concepts

Asymmetric or Public Key Cryptography



Cryptography concepts

Asymmetric or Public Key Cryptography



Cryptography concepts

- Advantages
  - Easier Key management
  - Easier key distribution
  - Less number of keys needed (O(n))
- Disadvantages
  - Relatively slower and complex
  - Management of public keys

Encryption Algorithms

Module 19

1. Ciphers

Module 19

1.1. Classical Cryptosystem

Module 19

Encryption Algorithms

Classical Cryptosystem

- It manipulates traditional characters, i.e., letters and digits directly.
- Based on symmetric key encryption scheme.
- It is mainly based on '*security through obscurity*'. The techniques employed for coding were kept secret and only the parties involved in communication knew about them.
- It requires the entire cryptosystem for communicating confidentially.
- **Consists of two types of Ciphers:**
  - **Substitution Cipher**
  - **Transposition Cipher**

Encryption Algorithms

Substitution Cipher

- Any character of plain text from the given fixed set of characters is substituted by some other character from the same set or different depending on a key.
- For example with a shift of 1, A would be replaced by B, B would become C, and so on.

$$E_n(x) = (x + n) mod\ 26$$

(Encryption Phase with shift n)

$$D_n(x) = (x - n) mod\ 26$$

(Decryption Phase with shift n)

Encryption Algorithms

Substitution Cipher

- Example
  - *Plain Text*: I am studying Data Encryption
  - *Key*: 4
  - *Output*: M eq wxyhCmrk Hexe IrgvCtxmsr
  - “ABCD” -> “PQRS”

Encryption Algorithms

Substitution Cipher

- *Types*
  - Caesar Cipher
  - Monoalphabetic Cipher
  - Polyalphabetic Cipher
    - Vigenere Cipher
    - Vernam Cipher
  - Playfair Cipher
  - Hill Cipher
  - One time Pad

Encryption Algorithms

Caesar Cipher

- Simplest monoalphabetic form of substitution cipher scheme.
- Generally referred to as the **Shift Cipher**. The concept is to replace each alphabet by another alphabet which is 'shifted' by some fixed number between 0 and 25.
- This is a special case of Shift cipher, with shift equal to 3.

Ciphertext Alphabet	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
Plainrtext Alphabet	x	y	z	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w

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

Monoalphabetic Ciphers

- Monoalphabetic cipher is a substitution cipher in which for a given key, the cipher alphabet for each plain alphabet is fixed throughout the encryption process.
- For example, if ‘A’ is encrypted as ‘D’, for any number of occurrence in that plaintext, ‘A’ will always get encrypted to ‘D’.
- Let **plaintext**= “This is the last warning”. With shift of 3, it’s **ciphertext**=“Wklv lv wkh odvw zduqlqj”.
- Plaintext char to ciphertext char relationship is *one to one*.
- Highly susceptible to cryptanalysis.

Encryption Algorithms

Polyalphabetic Ciphers

- Polyalphabetic Cipher is a substitution cipher in which the cipher alphabet for the plain alphabet may be different at different places during the encryption process.
- **Playfair and Vigenere Cipher are polyalphabetic ciphers**.
- **For example, plaintext**=“Banana”, **ciphertext**=“Ozipbe”
- Plaintext char to ciphertext char relationship is *one to many*.
- Complex and more secure than monoalphabetic.

Playfair Cipher

- The **Playfair cipher** was the first practical digraph substitution cipher invented in **1854** by **Charles Wheatstone** but was named after *Lord Playfair* who promoted the use of the cipher.
- It was used for tactical purposes by British forces in the Second Boer War and in World War I and for the same purpose by the Australians during World War II. This was because Playfair is reasonably fast to use and requires no special equipment.

Encryption Algorithms

Playfair Ciphers

- Let's take *key*="monarchy", *plaintext*="instruments".
- **Algorithm: (2 steps)**
  - **Generate the key Square(5×5):**

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

Encryption Algorithms

Playfair Ciphers

- **Algorithm to encrypt the plain text:** The plaintext is split into pairs of two letters (digraphs). If there is an odd number of letters, a Z is added to the last letter.
- **PlainText: "instruments"**
- **After Split: 'in' 'st' 'ru' 'me' 'nt' 'sz'**
- If two letters in a pair are same, add 'x' between them.
- **PlainText: "steep" => split: 'st' 'ex' 'ep'**

Encryption Algorithms

Playfair Ciphers

Rules for Encryption

- **If both the letters are in the same column**: Take the letter below each one (going back to the top if at the bottom).
- **If both the letters are in the same row**: Take the letter to the right of each one (going back to the leftmost if at the rightmost position).
- **If neither of the above rules is true**: Form a rectangle with the two letters and take the letters on the horizontal opposite corner of the rectangle.

Encryption Algorithms

Ciphertext: **gatlmzclrqtx**

Playfair Cipher

in:

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

st:

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

ru:

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

me:

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

nt:

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

sz:

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

Encryption Algorithms

Vigenere Cipher

- Simple form of polyalphabetic substitution, developed *by Blaise de Vigenere* (16th century mathematician)
- Input : *Plaintext* :   GEEKSFORGEEKS
- *Keyword* : AYUSH
- The given keyword is repeated in a circular manner until it matches the length of the plain text.

G	E	E	K	S	F	O	R	G	E	E	K	S
A	Y	U	S	H	A	Y	U	S	H	A	Y	U

Encryption Algorithms

Vigenere Cipher

Ciphertext : GCYCZFMLYLEIM

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

Vigenere Cipher

- There are two special cases of Vigenere cipher –
  - The keyword length is same as plaintext message. This case is called **Vernam Cipher**. It is more secure than typical Vigenere cipher.
  - Vigenere cipher becomes a cryptosystem with perfect secrecy, which is called **One-time pad**.

Encryption Algorithms

One Time Pad

- It is an unbreakable cipher.
- The key is exactly same as the length of message which is encrypted.
- The key is made up of random symbols.
- As the name suggests, key is used one time only and never used again for any other message to be encrypted.

Encryption Algorithms

One Time Pad

Plain text: T H I S I S S E C R E T
OTP-Key : X V H E U W N O P G D Z

Ciphertext: Q C P W C O F S R X H S
In groups : QCPWC OFSRX HS

Security: Let us say, we encrypt the name “point” with a one-time pad. It is a 5 letter text. To break the ciphertext by brute force, you need to try all possibilities of keys and conduct computation for (26 x 26 x 26 x 26 x 26) = 26^5 = 11881376 times. That’s for a message with 5 alphabets. Thus, for a longer message, the computation grows exponentially with every additional alphabet. This makes it computationally impossible to break the ciphertext by brute force.

Encryption Algorithms

Transposition Cipher

- It is another type of cipher where the order of the alphabets in the plaintext is rearranged to create the ciphertext. The actual plaintext alphabets are not replaced.
- *For example*, "banana" is converted to "anbana"
- The *plaintext* is "golden statue is in eleventh cave" and the secret random *key* chosen is "five". We arrange this text horizontally in table with number of column equal to key value. The resulting text is shown below.

Encryption Algorithms

Transposition Cipher

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

- This will be read column wise as “gnunea oseenv ltilte daseh etivc”

Encryption Algorithms

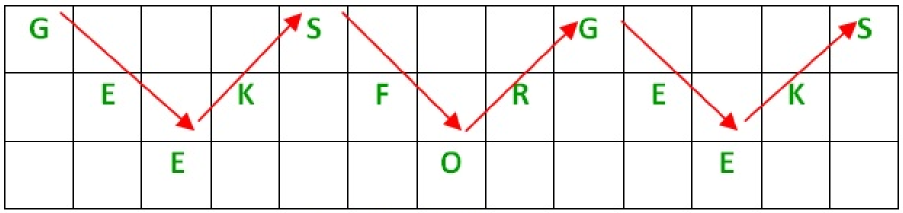
Transposition Cipher

- Rail Fence cipher
- Scytale
- Route cipher
- Columnar transposition
- Double transposition
- Myszkowski transposition

Encryption Algorithms

Rail fence Cipher

- In the rail fence cipher, the plain-text is written downwards and diagonally on successive rails of an imaginary fence.
- When we reach the bottom rail, we traverse upwards moving diagonally, after reaching the top rail, the direction is changed again. Thus the alphabets of the message are written in a zig-zag manner.
- After each alphabet has been written, the individual rows are combined to obtain the cipher-text.



Rail fence Cipher

- *Message* is “GeeksforGeeks” and the *number of rails* = 3
- *Ciphertext: “gsgsekfrekeoe”*
- *Number of columns* in rail fence cipher remains equal to the *length of plain-text* message.
- *Decryption:* Then, we fill the cipher-text row wise. After filling it, we traverse the matrix in zig-zag manner to obtain the original text.

Hence original matrix will be of 3*12 , now marking places with text as '*' we get

```
* _ _ _ * _ _ _ * _ _ _ *
_ * _ * _ * _ * _ * _ *
_ _ * _ _ _ *  _ _ _ * _
```

Columnar Transposition Cipher

- Columnar Transposition involves writing the plaintext out in rows, and then reading the ciphertext off in columns one by one. **Algorithm**:
  - The message is written out in rows of a fixed length, and then read out again column by column, and the columns are chosen in some scrambled order.
  - Width of the rows and the permutation of the columns are usually defined by a keyword.
  - ***For example***, the word **HACK** is of length 4 (so the rows are of length 4), and the permutation is defined by the alphabetical order of the letters in the keyword. In this case, the ***order*** would be "3 1 2 4".
  - Any spare spaces are filled with nulls or left blank or placed by a character (Example: _).
  - Finally, the message is read off in columns, in the order specified by the keyword.

Encryption Algorithms

Encryption

Given text = Geeks for Geeks

Keyword = HACK   **Length of Keyword** = 4 (no of rows)   **Order of Alphabets in HACK** = 3124

H	A	C	K
3	1	2	4
G	e	e	k
s	_	f	o
r	_	G	e
e	k	s	_

Print Characters of column 1,2,3,4

Encrypted Text = e kefGsGsrekoe_

Encryption Algorithms

Double Transposition Cipher

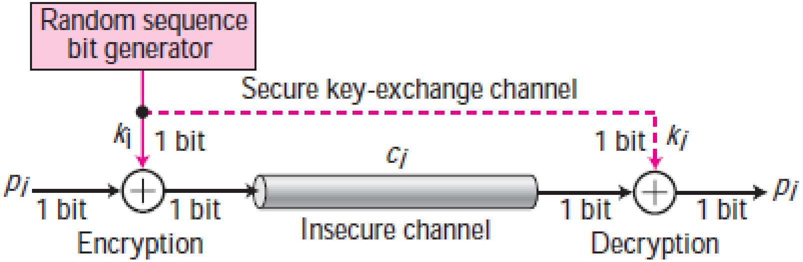
- This was one of the most secure hand ciphers used in the Second World War.
- Double Transposition consists of two applications of ***columnar transposition*** to a message. The two applications may use the same key for each of the two steps, or they may use different keys.
- To decrypt a double transposition, construct a block with the right number of rows under the keyword, blocking off the short columns. Write the cipher in by columns, and read it out by rows. Lather, rinse, repeat.

1.2. Modern Cryptosystem

Module 19

Encryption Algorithms

- **Stream Cipher**
  - Symmetric Key cipher
  - Encrypt the message as a sequence of bytes
  - Encrypt the data a bit or byte at a time



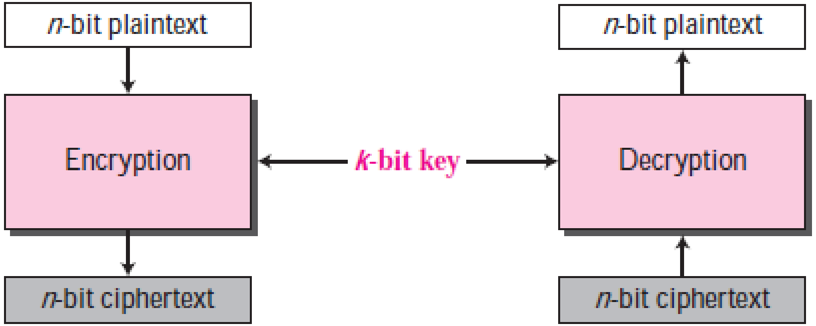
Encryption Algorithms

Stream Cipher

In text format	In binary format	
Blue Sky	010111001	Plain Text
+	100101011	XOR Operation with key
ZTU91^%D	110010010	Cipher Text

Encryption Algorithms

- Block Cipher
  - Symmetric Key cipher
  - Divide a message into fixed size blocks (64 or 128-bit)
  - Encrypt each block individually
  - Integrate all the outputs to obtain final ciphertext

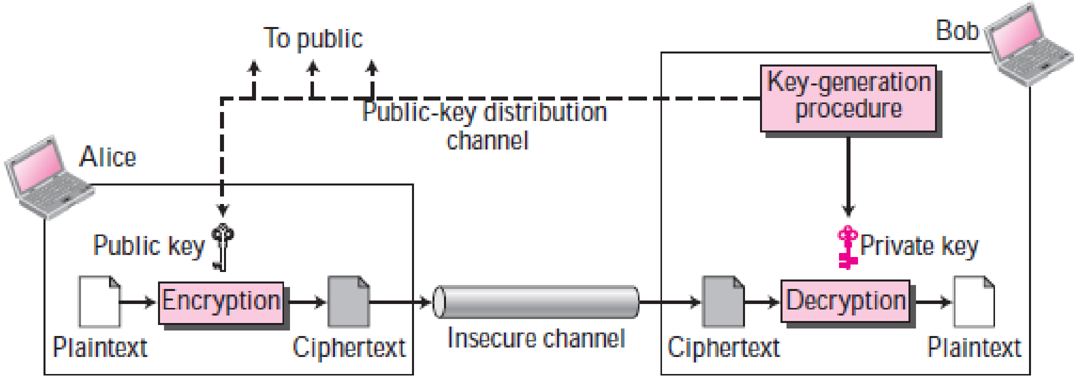


Encryption Algorithms

Block cipher	Stream cipher
Block Cipher Converts the plain text into cipher text by taking plain text's block at a time.	Stream Cipher Converts the plain text into cipher text by taking 1 byte of plain text at a time.
Uses either 64 bits or more	While stream cipher uses 8 bits.
The complexity is simple.	More complex.
Uses confusion as well as diffusion.	Uses only confusion.
Reverse encrypted text is hard.	Reverse encrypted text is easy.
ECB (Electronic Code Book) and CBC (Cipher Block Chaining)	CFB (Cipher Feedback) OFB (Output Feedback)
The main implementation of Block Cipher is Feistel Cipher.	Main implementation of Stream Cipher is Vernam Cipher.
Slower	Faster

Encryption Algorithms

- ## Asymmetric Key Ciphers
  - Symmetric-key cryptography is based on sharing secrecy, asymmetric-key cryptography is based on personal secrecy.
  - In symmetric-key, symbols are permuted or substituted, in asymmetric-key, numbers are manipulated.



Encryption Algorithms

Shannon’s Theory of confusion and diffusion

- Introduced to prevent cryptanalysis, based on ***statistical analysis*** (frequency analysis, etc.) to deduce plaintext from ciphertext, or generating key.
- He **suggested two methods** to achieve this:
  - **Confusion**
  - **Diffusion**
- **Confusion** and **diffusion** area unit the properties for creating a secure cipher.

Encryption Algorithms

Shannon's Theory of confusion and diffusion

- **Diffusion**: Hide the relationship between plaintext and ciphertext. If a single bit in plaintext is changed, several or all characters in the ciphertext must change.
- **Confusion**: Hide the relationship between key and ciphertext. If a single bit in key is changed, several or all characters in the ciphertext must change.
- *Confusion* is employed for making uninformed cipher text whereas *diffusion* is employed for increasing the redundancy of the plain text over the foremost a part of the cipher text to create it obscure. The diffusion is solely employed by block cipher, or else, confusion is employed by each stream and block cipher.

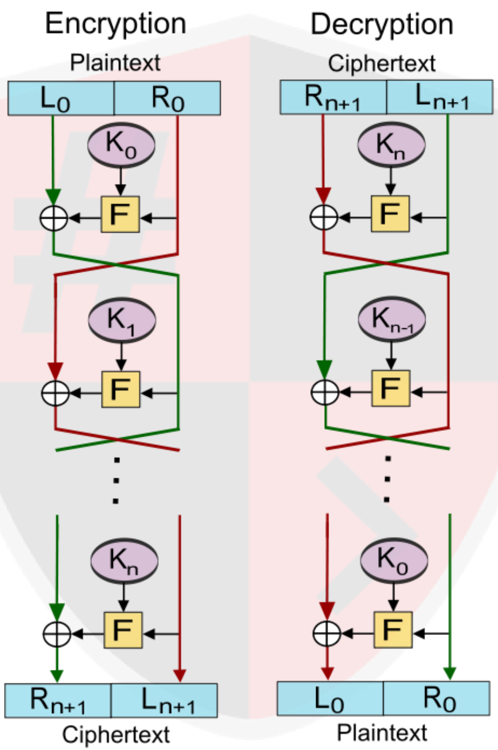
2. Fiestel Cipher

Module 19

Encryption Algorithms

- It is a design model from which many different block ciphers are derived. DES is just one example of a Feistel Cipher.
- The encryption process uses the Feistel structure consisting multiple rounds of processing of the plaintext, each round consisting of a "substitution" step followed by a permutation step.
- The input block to each round is divided into two halves that can be denoted as L and R for the left half and the right half.
- In each round, the right half of the block, R, goes through unchanged. But the left half, L, goes through an operation that depends on R and the encryption key, they are swapped at the end of the round.

Encryption Algorithms



Encryption Algorithms

- In real implementation of the Feistel Cipher, such as ***DES***, instead of using the whole encryption key during each round, a round-dependent key (a ***subkey***) is derived from the encryption key. This means that each round uses a different key, although all these subkeys are related to the original key.
- The permutation step at the end of each round swaps the modified L and unmodified R. Therefore, the L for the next round would be R of the current round. And R for the next round be the output L of the current round.
- The number of rounds are specified by the algorithm design.
- Once the last round is completed then the two sub blocks, ‘R’ and ‘L’ are concatenated in this order to form the ciphertext block.

3. Data Encryption Standard (DES)

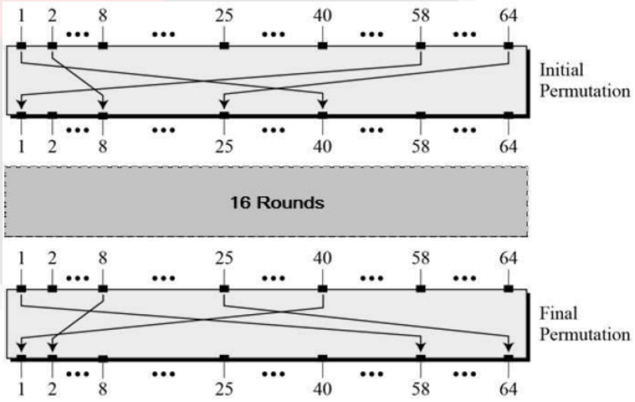
Module 19

Encryption Algorithms

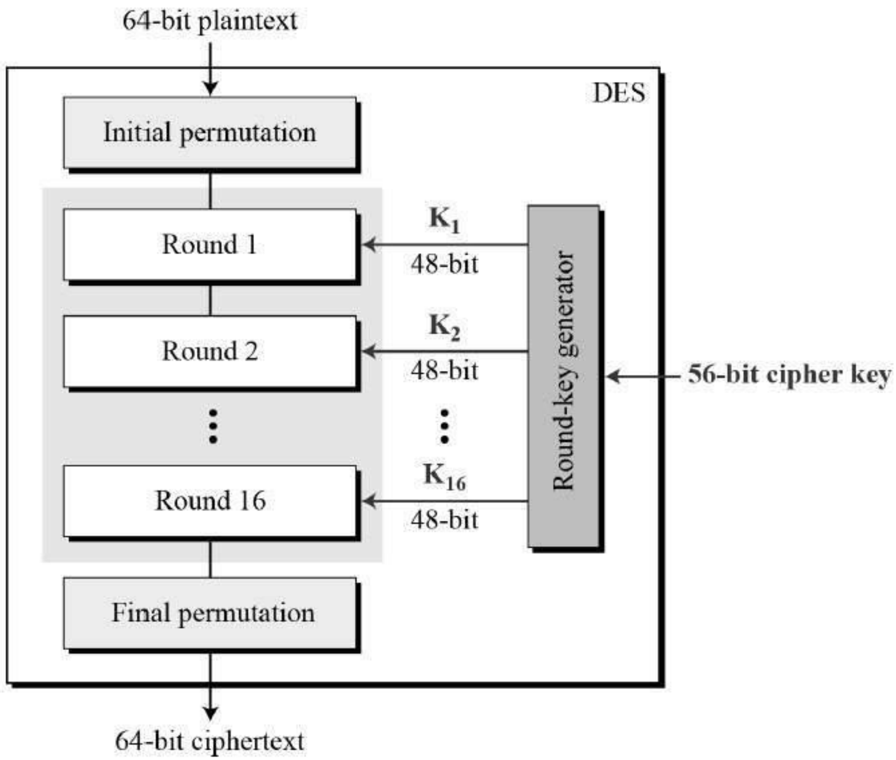
- The Data Encryption Standard (DES) is a symmetric-key block cipher published by the *National Institute of Standards and Technology* (NIST).
- DES is an implementation of a Feistel Cipher. It uses 16 round Feistel structure. The block size is 64-bit. Though, key length is 64-bit, DES has an effective key length of 56 bits.
- DES is the archetypal block cipher - an algorithm that takes a fixed-length string of plaintext bits and transforms it into a ciphertext bitstring of the same length.
- Due to the inherent weakness of DES with today's technologies, some organizations repeat the process three times (3DES) for added strength, until they can afford to update their equipment to AES capabilities.

Encryption Algorithms

- Since DES is based on the Feistel Cipher, all that is required to specify DES is –
  - Round function
  - Key schedule
  - Any additional processing – Initial and final permutation

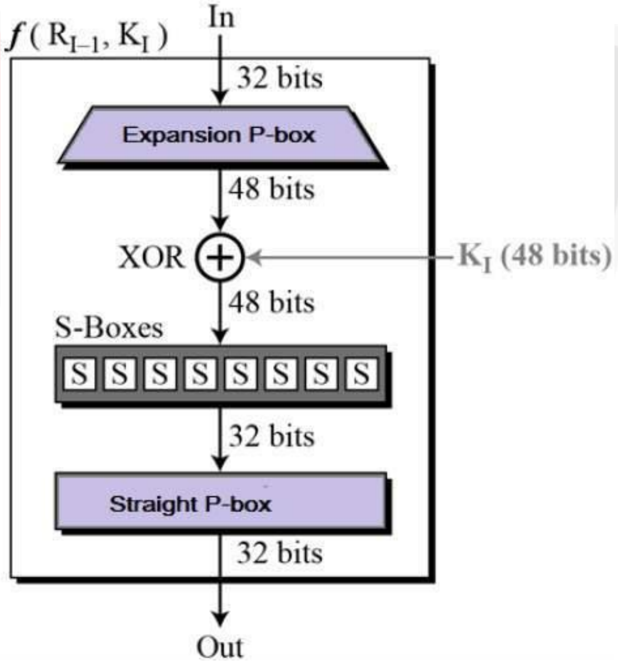


Encryption Algorithms



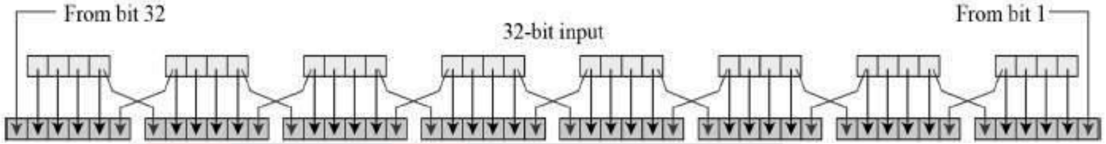
Encryption Algorithms

Round function



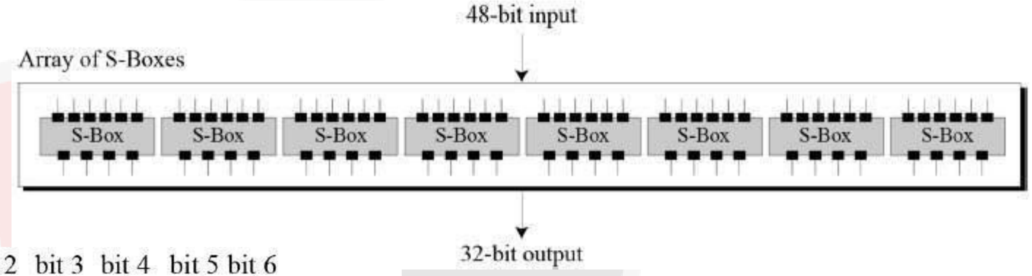
Encryption Algorithms

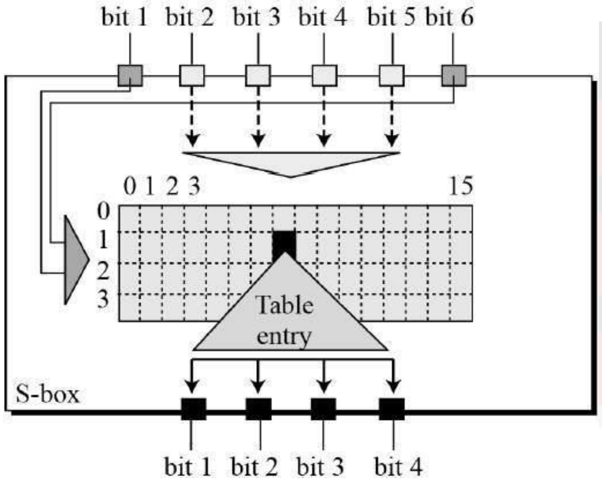
Expansion Permutation function



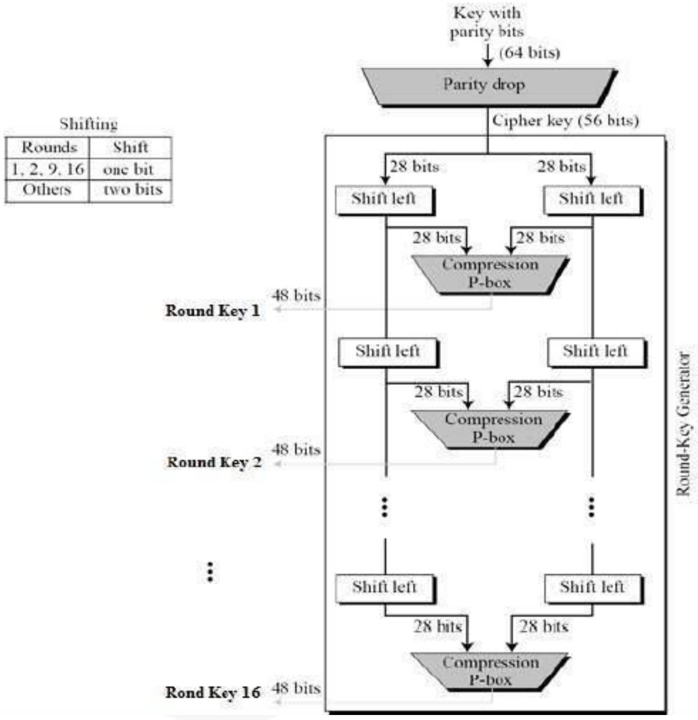
32	01	02	03	04	05
04	05	06	07	08	09
08	09	10	11	12	13
12	13	14	15	16	17
16	17	18	19	20	21
20	21	22	23	24	25
24	25	26	27	28	29
28	29	31	31	32	01

Substitution box





Key Generation



DES Analysis

- The DES satisfies both the desired properties of block cipher. These two properties make cipher very strong.
  - **Avalanche effect** – A small change in plaintext results in the very great change in the ciphertext.
  - **Completeness** – Each bit of ciphertext depends on many bits of plaintext.
- DES has proved to be a very well designed block cipher. There have been no significant cryptanalytic attacks on DES other than exhaustive key search.

4. Attacks on DES

Module 19

Encryption Algorithms

Weaknesses

- **Weak key**
  - **Key Size**: 56 bits (Exhaustive Key Search: 2^56)
    - Four keys out of 2^56 are weak: all 0s, all 1s, half 0s, half 1s
  - **Semi weak keys**: Only two different round keys
  - **Possible weak keys**: Only four different round keys
- **Cipher design**
  - **S-box**: Two specifically chosen i/p can create same o/p through S-box.

Encryption Algorithms

Brute Force

- Diffie and Hellman proposed a machine costing an estimated US$20 million which could find a DES key in a single day
- The feasibility of cracking DES quickly was demonstrated in 1998 when a custom DES-cracker was built by the Electronic Frontier Foundation, at the cost of approximately US$250,000
- The machine brute-forced a key in a little more than 2 days' worth of searching.

Encryption Algorithms

Linear Cryptanalysis

- Discovered by Mitsuru Matsui, and needs 2^{43} known plaintexts, based on finding affine approximations to the action of a cipher.
- It was the first experimental cryptanalysis of the cipher reported in the open community .
- Junod (2001) performed several experiments to determine the actual time complexity of linear cryptanalysis, and reported that it was somewhat faster than predicted, requiring time equivalent to 2^{39}–2^{41} DES evaluations.

Differential Cryptanalysis

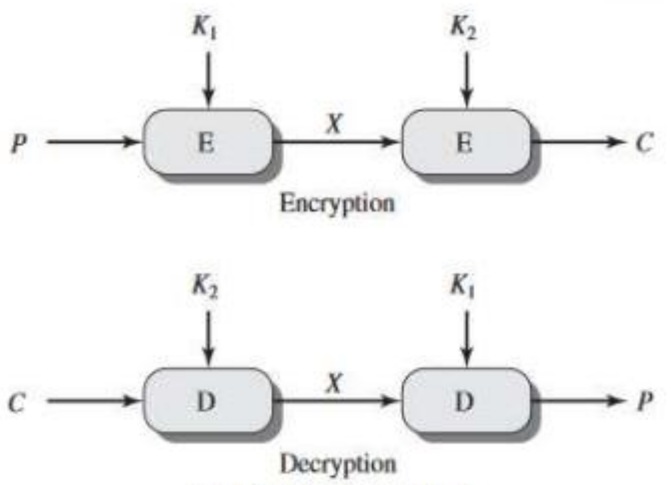
- Rediscovered in the late 1980s by Eli Biham and Adi Shamir; it was known earlier to both IBM and the NSA and kept secret. To break the full 16 rounds, differential cryptanalysis requires 2^{47} chosen plaintexts. DES was designed to be resistant to DC.
- Study of how differences in information input can affect the resultant difference at the output, with chosen plaintext
- Discovering where the cipher exhibits non-random behavior, and exploiting such properties to recover the secret key (cryptography key).

4. Advancements in DES

Module 19

Encryption Algorithms

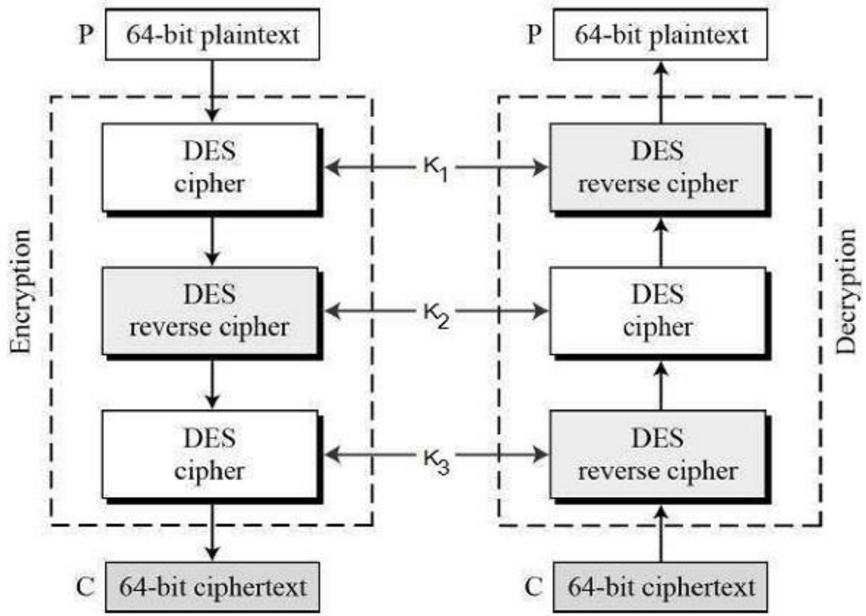
Double DES



(a) Double encryption

Encryption Algorithms

Triple DES (3DES)



5. Advanced Encryption Standard (AES)

Module 19

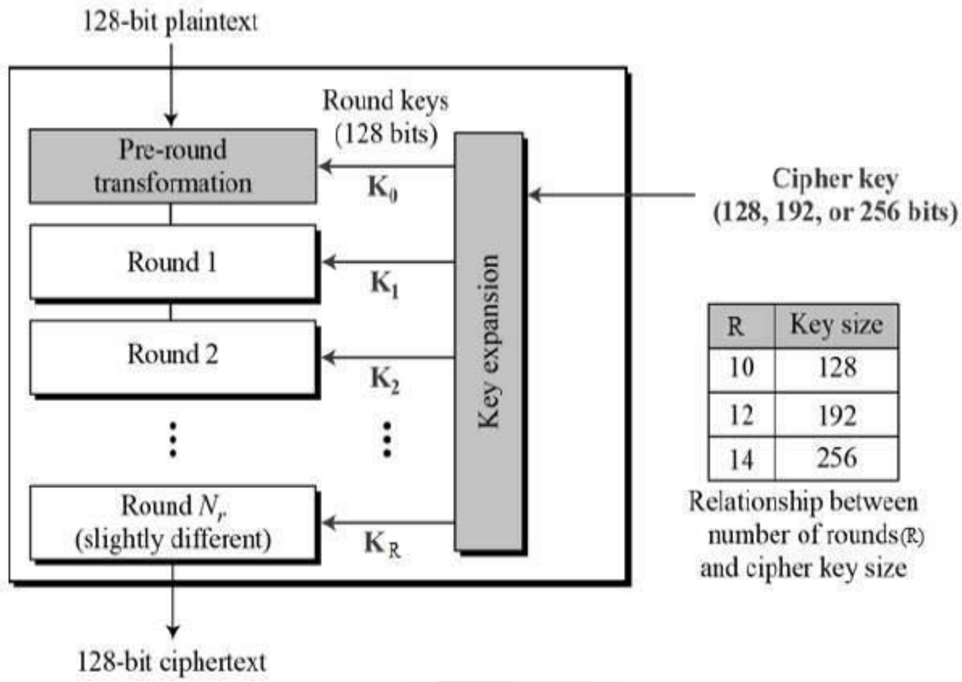
Encryption Algorithms

- The more popular and widely adopted symmetric encryption algorithm. It is found at least six time faster than triple DES.
- The **features** of AES are as follows –
  - Symmetric key block cipher
  - 128-bit block data, 128/192/256-bit keys
  - Stronger and faster than Triple-DES
  - Provide full specification and design details
  - Software implementable in C and Java

Encryption Algorithms

- It is based on Rjindael cipher structure, or ‘substitution–permutation network’.
- AES treats the 128 bits of a plaintext block as 16 bytes, arranged in four columns and four rows for processing as a matrix, called state (array).
- The number of rounds in AES is variable and depends on the length of the key
  - 10 rounds for 128-bit keys,
  - 12 rounds for 192-bit keys and
  - 14 rounds for 256-bit keys
- Till date, no practical cryptanalytic attacks against AES has been discovered.

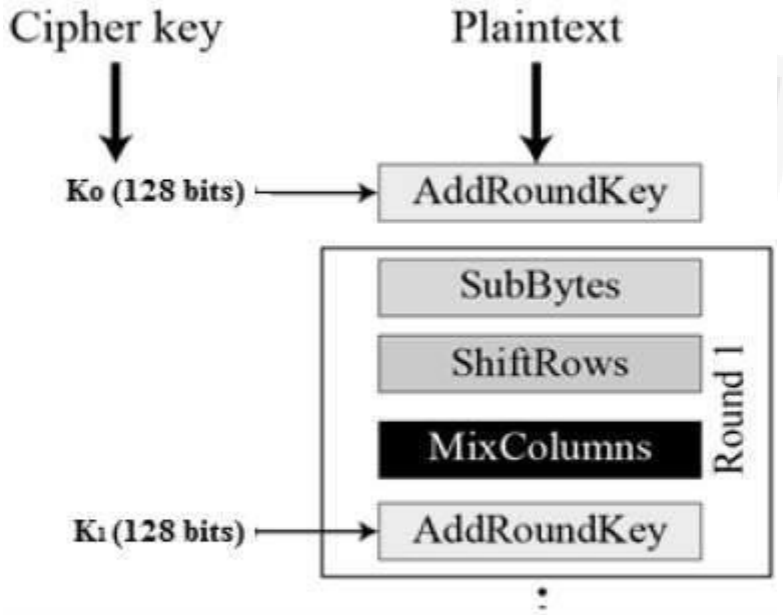
Encryption Algorithms



R	Key size
10	128
12	192
14	256

Relationship between number of rounds(R) and cipher key size

Encryption Algorithms



Single Round:

- **Byte Substitution (SubBytes):** The 16 input bytes are substituted by looking up a fixed table (S-box) given in design. The result is in a matrix of four rows and four columns.
- **Shiftrows:** Each of the four rows of the matrix is shifted to the left, circular
  - First row is not shifted.
  - Second row is shifted one (byte) position to the left.
  - Third row is shifted two positions to the left.
  - Fourth row is shifted three positions to the left.

Single Round:

- **MixColumns:** Each column of four bytes is now transformed using a special mathematical function. This function takes as input the four bytes of one column and outputs four completely new bytes, which replace the original column. The result is another new matrix consisting of 16 new bytes. It should be noted that this step is not performed in the last round.
- **Addroundkey:** The 16 bytes of the matrix are now considered as 128 bits and are XORed to the 128 bits of the round key. If this is the last round then the output is the ciphertext. Otherwise, the resulting 128 bits are interpreted as 16 bytes and we begin another similar round.

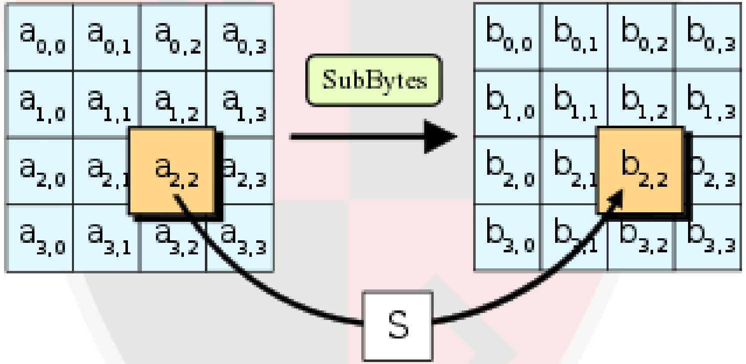
Encryption Algorithms

AES State

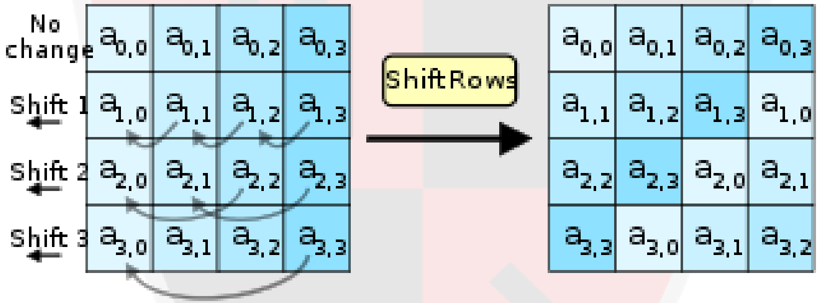
$$\begin{bmatrix} b_0 & b_4 & b_8 & b_{12} \\ b_1 & b_5 & b_9 & b_{13} \\ b_2 & b_6 & b_{10} & b_{14} \\ b_3 & b_7 & b_{11} & b_{15} \end{bmatrix}$$

Encryption Algorithms

SubBytes

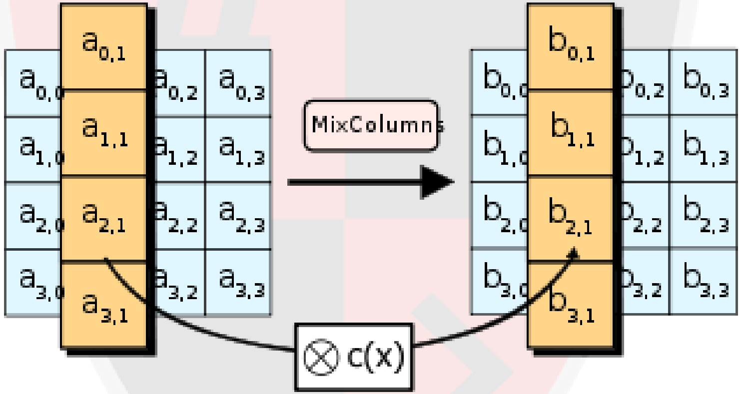


ShiftRows



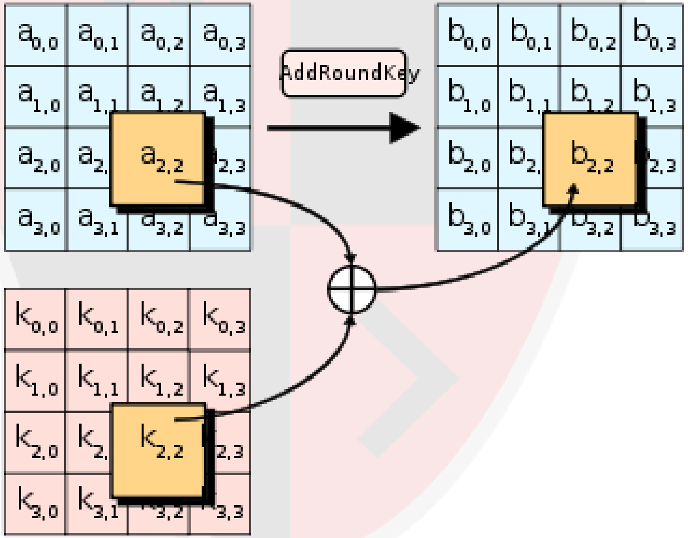
Encryption Algorithms

MixColumns



Encryption Algorithms

AddRoundKey



Encryption Algorithms

Strength of AES:

- In present day cryptography, AES is widely adopted and supported in both hardware and software.
- Till date, no practical cryptanalytic attacks against AES has been discovered.
- Additionally, AES has built-in flexibility of key length, which allows some ‘future-proofing’ against progress in exhaustive key searches.
- However, just as for DES, the AES security is assured only if it is correctly implemented and good key management is employed.

Encryption Algorithms

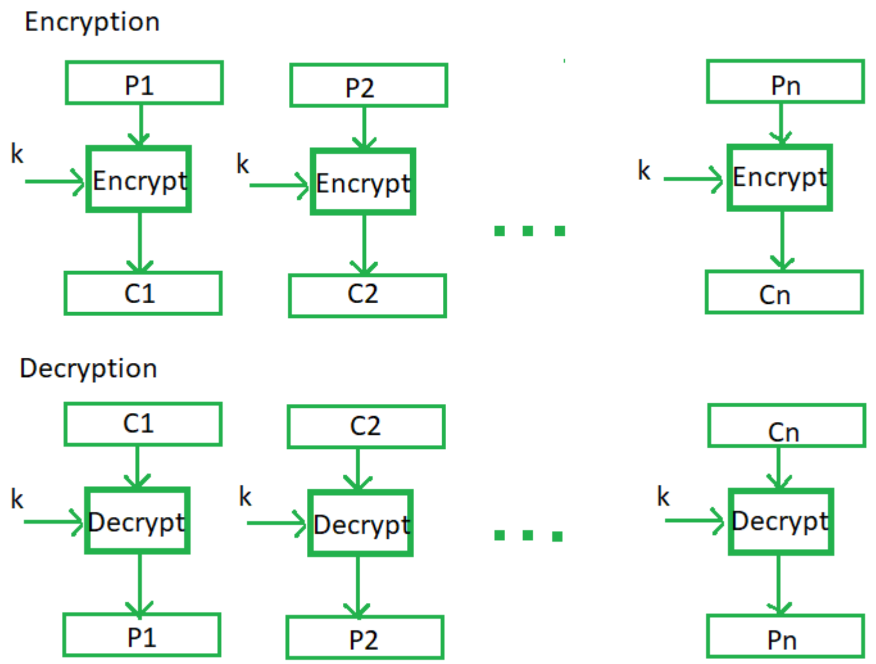
AES	DES
Key length can be of 128-bits, 192-bits and 256-bits.	Key length is 56 bits in DES.
Number of rounds depends on key length	16 rounds of identical operations
The structure is based on substitution-permutation network.	The structure is based in feistal network.
AES is more secure than the DES cipher and is the de facto world standard.	DES can be broken easily as it has known vulnerabilities. 3DES is more secure
AES can encrypt 128 bits of plaintext.	DES can encrypt 64 bits of plaintext
AES was designed by Vincent Rijmen and Joan Daemen.	DES was designed by IBM.
No known crypt-analytical attacks against AES but side channel attacks against AES implementations possible.	Known attacks against DES include : Brute-force, Linear crypt-analysis and Differential crypt-analysis.

6. Block Cipher Modes of Operation

Module 19

Encryption Algorithms

Electronic Code Book (ECB)



Encryption Algorithms

Advantages

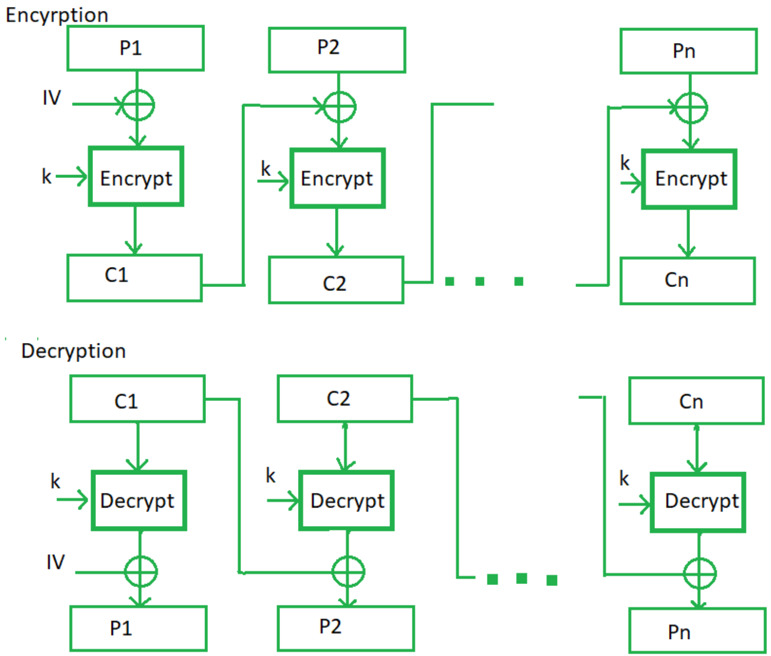
- Parallel encryption of blocks of bits is possible
- Simple

Disadvantages

- Prone to cryptanalysis since there is a direct relationship between plaintext and ciphertext.
- Two same blocks give same ciphertext

Encryption Algorithms

Cipher Block Chaining (CBC)

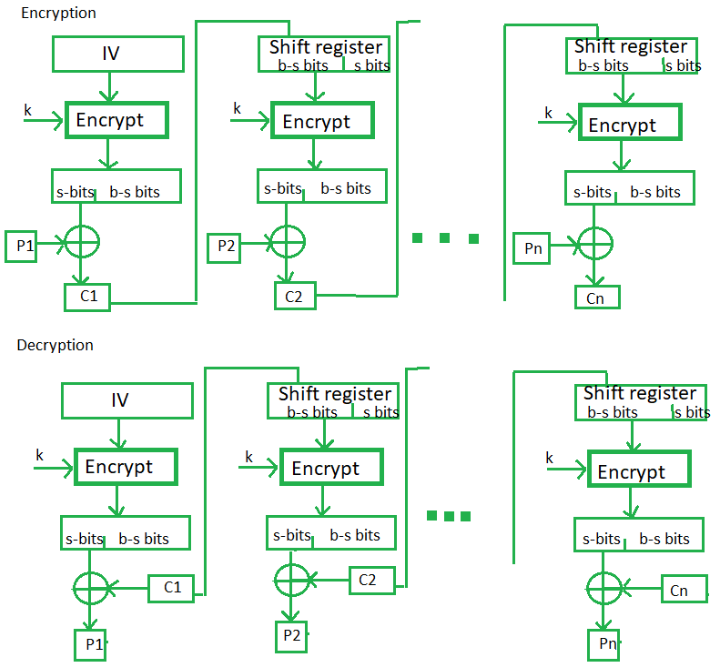


Encryption Algorithms

- Advantages
  - CBC works well for input greater than *b* bits.
  - CBC is a good authentication mechanism.
  - Better resistive nature towards cryptanalsis than ECB.
- Disadvantages
  - Parallel encryption is not possible since every encryption requires previous cipher.

Encryption Algorithms

Cipher Feedback Mode (CFB)

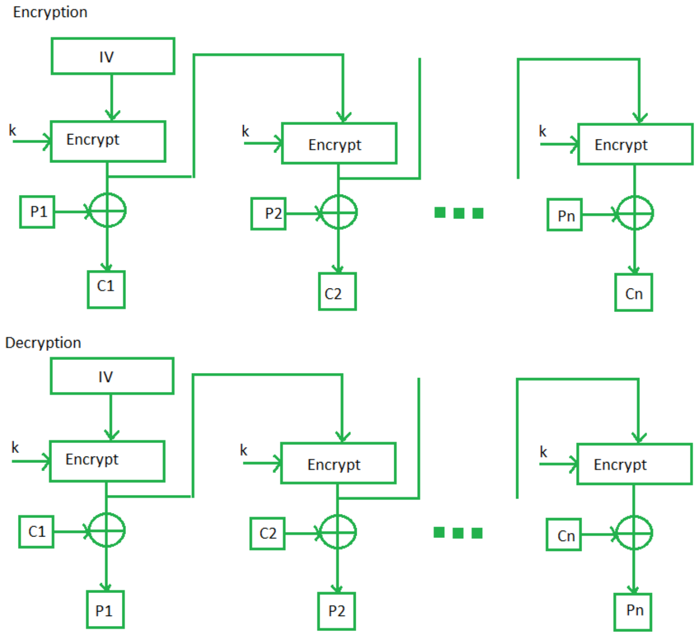


Encryption Algorithms

- **Advantages**
  - Since, there is some data loss due to use of shift register, thus it is difficult for applying cryptanalysis.
  - Randomness of IV not needed
- **Disadvantages**
  - Somewhat slower

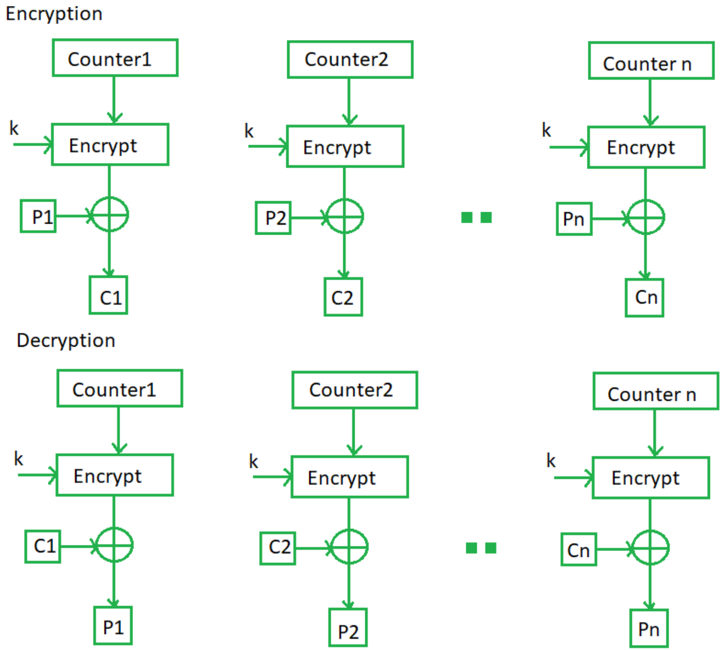
Encryption Algorithms

Output Feedback Mode(OFB)



Encryption Algorithms

Counter Mode (CTR)



Encryption Algorithms

- Advantages
  - Simple and fast
  - Does not propagate error of transmission
- Disadvantages
  - Requires a synchronous counter at sender and receiver.

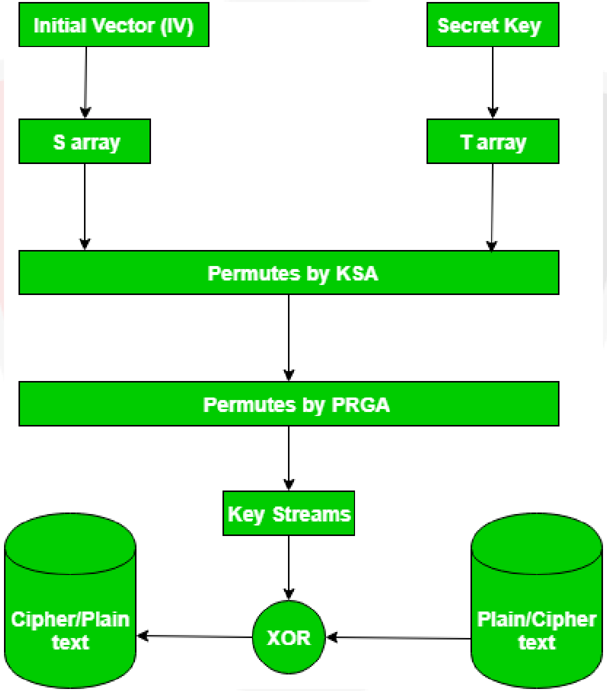
6. Stream Ciphers

Module 19

Encryption Algorithms

- **RC4** -- a variable key-size stream cipher with byte-oriented operations. The algorithm is based on the use of a random permutation.
- **RC5** -- a parameterized algorithm with a variable block size, a variable key size, and a variable number of rounds. Allowable choices for the block size are 32 bits, 64 bits and 128 bits. The number of rounds can range from 0 to 255, while the key can range from 0 bits to 2040 bits in size. RC5 has three routines: **key expansion**, **encryption**, and **decryption**.
- **RC6** -- a block cipher based on RC5. RC6 is a parameterized algorithm where the block size, the key size, and the number of rounds are variable. The upper limit on the key size is 2040 bits. RC6 adds two features to RC5: the inclusion of **integer multiplication** and the use of **four 4-bit working registers** instead of RC5's two 2-bit registers.

Encryption Algorithms



6. Public Key Cryptography

Module 19

Encryption Algorithms

Rivest Shamir Adleman (RSA) Algorithm

- Based on the fact that finding the factors of a large composite number is difficult: when the factors are prime numbers
- RSA involves a public key and private key. The public key can be known to everyone; it is used to encrypt messages. Messages encrypted using the public key can only be decrypted with the private key.
- Many protocols like Secure Shell, OpenPGP, S/MIME, and SSL/TLS rely on RSA for encryption and digital signature functions.

Encryption Algorithms

1. Choose two different large random prime numbers p and q
2. Calculate $n = pq$
   - n is the modulus for the public key and the private keys
3. Calculate the totient: $\phi(n) = (p-1)(q-1)$.
4. Choose an integer e such that 1 < e < $\phi(n)$, and e is co-prime to $\phi(n)$ i.e.: e and $\phi(n)$ share no factors other than 1; gcd(e, $\phi(n)$) = 1.
   - e is released as the public key exponent
5. Compute d to satisfy the congruence relation $de \equiv 1 \pmod{\phi(n)}$ i.e.: $de = 1 + x\phi(n)$ for some integer x. (Simply to say : Calculate $d = (1 + x\phi(n))/e$ to be integer)
   - d is kept as the private key exponent

Encryption Algorithms

Notes on the above steps:

- Step 1: Numbers can be probabilistically tested for primality.
- Step 3: changed in PKCS#1 (en) v2.0 to $\lambda(n) = \mathrm{lcm}(p-1, q-1)$ instead of $\phi(n) = (p-1)(q-1)$.
- Step 4: A popular choice for the public exponents is e = 2^{16} + 1 = 65537. Some applications choose smaller values such as e = 3, 5, or 35 instead. This is done to make encryption and signature verification faster on small devices like smart cards but small public exponents may lead to greater security risks.
- Steps 4 and 5 can be performed with the extended Euclidean algorithm (en); see modular arithmetic.

The **public key** is made of the modulus n and the public (or encryption) exponent e.

The **private key** is made of p,q and the private (or decryption) exponent d which must be kept secret.

Encryption Algorithms

Encrypting message [change | change source]

Alice gives her public key (n & e) to Bob and keeps her private key secret. Bob wants to send message **M** to Alice.

First he turns **M** into a number m smaller than n by using an agreed-upon reversible protocol known as a padding scheme. He then computes the ciphertext c corresponding to:

$$c = m^e \mod n$$

This can be done quickly using the method of exponentiation by squaring. Bob then sends c to Alice.

Decrypting message [change | change source]

Alice can recover m from c by using her private key d in the following procedure:

$$m = c^d \bmod n$$

Given m, she can recover the original distinct prime numbers, applying the Chinese remainder theorem to these two congruences yields

$$m^{ed} \equiv m \bmod pq.$$

Thus,

$$c^d \equiv m \bmod n.$$

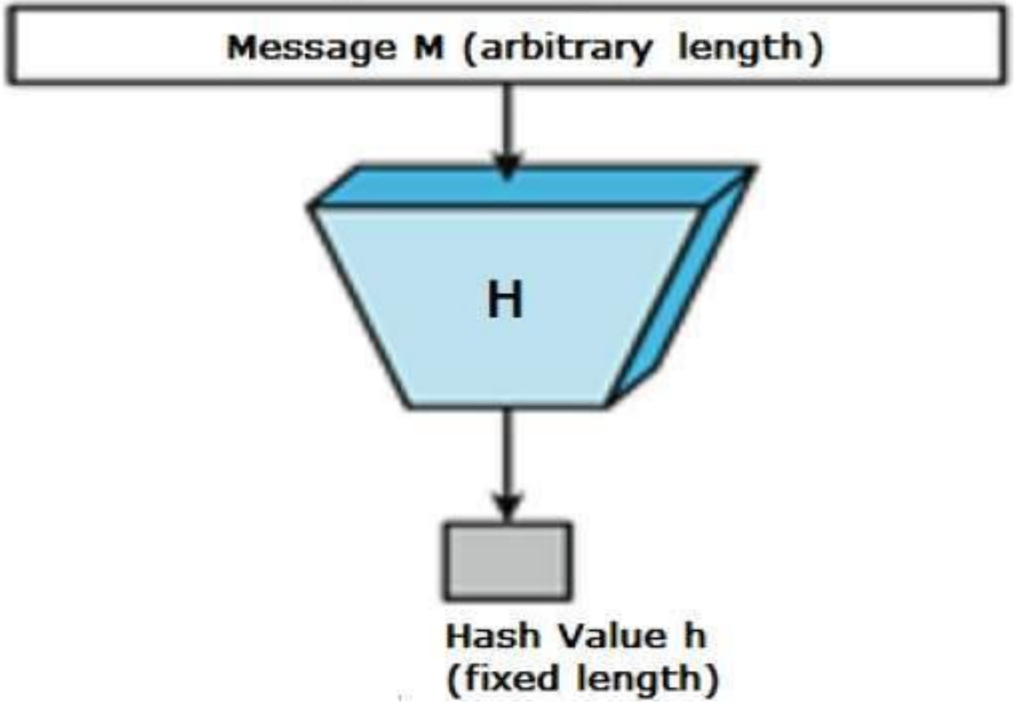
7. Message Digest (One-way Hash) Functions

Module 19

Encryption Algorithms

- A hash function is a mathematical function that converts a numerical input value into another compressed numerical value. The input to the hash function is of arbitrary length but output is always of fixed length.
- Values returned by a hash function are called **message digest** or simply **hash values**.
- Generally for any hash function h with input x, computation of h(x) is a fast operation.
- Computationally hash functions are much faster than a symmetric encryption.

Encryption Algorithms



Features

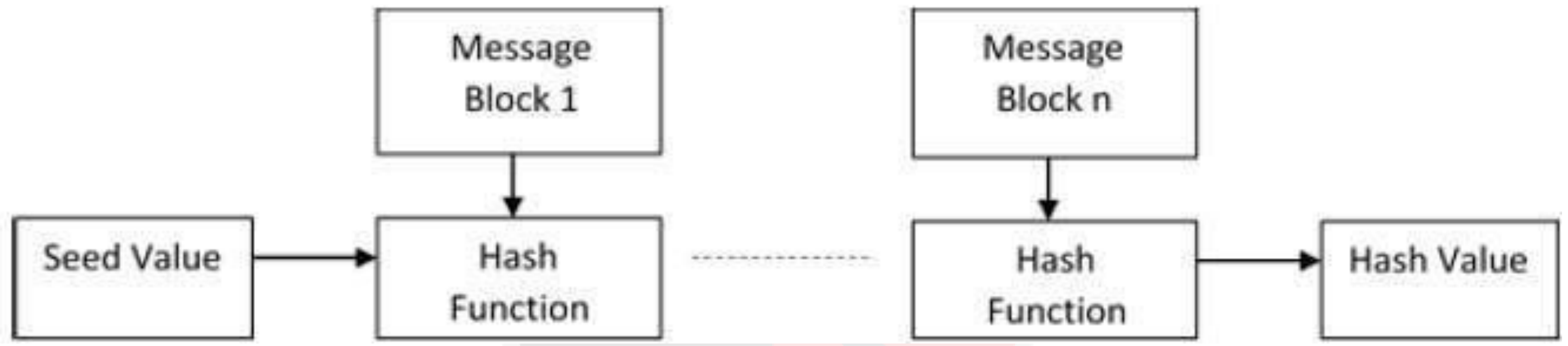
- Hash function converts data of arbitrary length to a fixed length. This process is often referred to as **hashing the data**.
- In general, the hash is much smaller than the input data, hence hash functions are sometimes called **compression functions**.
- Since a hash is a smaller representation of a larger data, it is also referred to as a **digest**.
- Hash function with n bit output is referred to as an **n-bit hash function**. Popular hash functions generate values between 160 and 512 bits.

Encryption Algorithms

Properties

- **Pre-Image Resistance:** This property means that it should be computationally hard to reverse a hash function.
- **Second Pre-Image Resistance:** This property means given an input and its hash, it should be hard to find a different input with the same hash.
- **Collision Resistance:** This property means it should be hard to find two different inputs of any length that result in the same hash. This property is also referred to as collision free hash function.

Encryption Algorithms



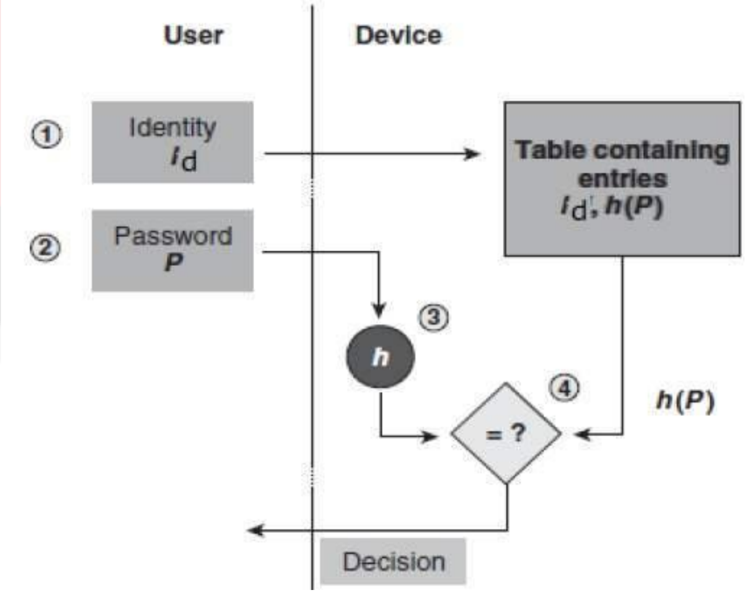
Encryption Algorithms

Popular Hash Functions

- **Message Digest (MD):** MD2, MD4, MD5 and MD6. It was adopted as Internet Standard RFC 1321. It is a 128-bit hash function. In 2004, collisions were found in MD5, and an analytical attack was reported to be successful only in an hour by using computer cluster.
- **Secure Hash Function (SHA):** SHA-0, SHA-1, SHA-2, and SHA-3. SHA-2 family has four further SHA variants, SHA-224, SHA-256, SHA-384, and SHA-512. No successful attacks have yet been reported on SHA-2 hash function.
- **RIPEMD:** RACE Integrity Primitives Evaluation Message Digest. The set includes RIPEND, RIPEMD-128, and RIPEMD-160. There also exist 256, and 320-bit versions of this algorithm.

Applications of Hash Functions

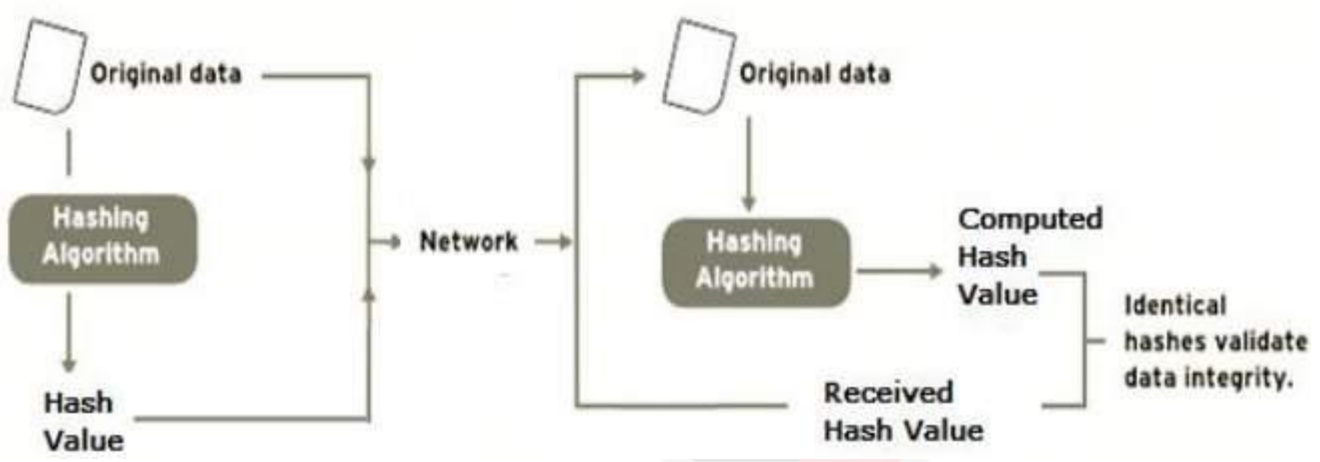
- Password Storage



Encryption Algorithms

Applications of Hash Functions

- Data Integrity Check (Digital Signatures)



8. Secure Hash Algorithm (SHA-256)

Module 19

Encryption Algorithms

- **SHA-2** (**Secure Hash Algorithm 2**) is a set of cryptographic hash functions designed by the United States National Security Agency (NSA)
- The SHA-2 family consists of six hash functions with digests (hash values) that are 224, 256, 384 or 512 bits: **SHA-224, SHA-256, SHA-384, SHA-512, SHA-512/224, SHA-512/256**.
- SHA-2 was published in 2001 by the National Institute of Standards and Technology
- Currently, the best public attacks break **preimage resistance** for 52 out of 64 rounds of SHA-256 or 57 out of 80 rounds of SHA-512, and **collision resistance** for 46 out of 64 rounds of SHA-256

Encryption Algorithms

Algorithm

Pre-processing

- **1. Padding**. If we note *M* the message to be hashed, and *l* its length in bits where $l < 2^{64}$, then as a first step we create the padded message *M'*, which is message *M* plus a right padding, such that *M'* is of length *l'*, a multiple of 512

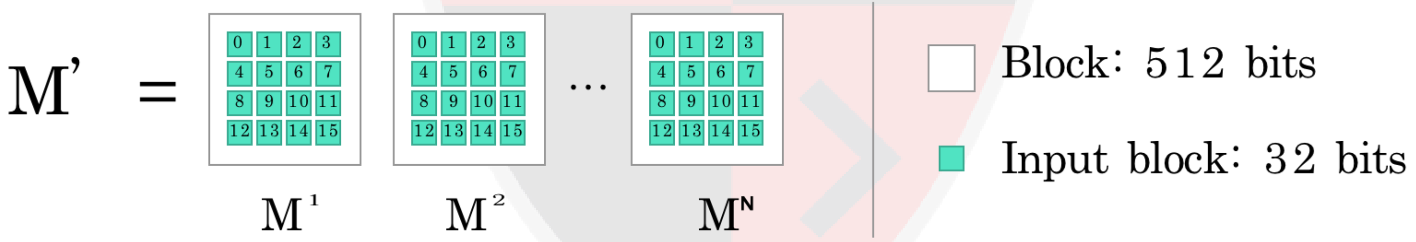
where P = 1 0..0 L

and L is M's length *l* in bit notation

Algorithm

Pre-processing

- **2. Blocks**. *M'* is parsed into *N blocks* of size 512 bits, M^1 to M^N, and each block is expressed as 16 *input blocks* of size 32 bits, M_0 to M_{15}.



Encryption Algorithms

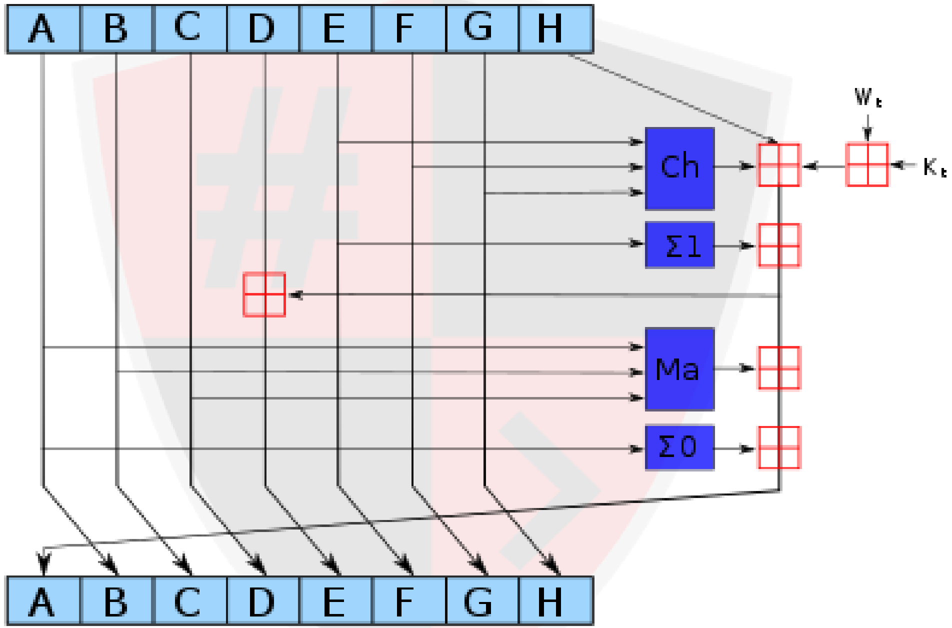
Algorithm

Pre-processing

- **3. Hash initialization**. The initial hash value H^0 of length 256 bits (8 input blocks of 32 bits) is set by taking the first 32 bits of the fractional parts of the square roots of the first eight prime numbers:

$$H_0^{(0)} = \texttt{6a09e667}$$
$$H_1^{(0)} = \texttt{bb67ae85}$$
$$H_2^{(0)} = \texttt{3c6ef372}$$
$$H_3^{(0)} = \texttt{a54ff53a}$$
$$H_4^{(0)} = \texttt{510e527f}$$
$$H_5^{(0)} = \texttt{9b05688c}$$
$$H_6^{(0)} = \texttt{1f83d9ab}$$
$$H_7^{(0)} = \texttt{5be0cd19}$$

Encryption Algorithms



9. Transport Layer Security

Module 19

Encryption Algorithms

SSL (Secure Sockets Layer)

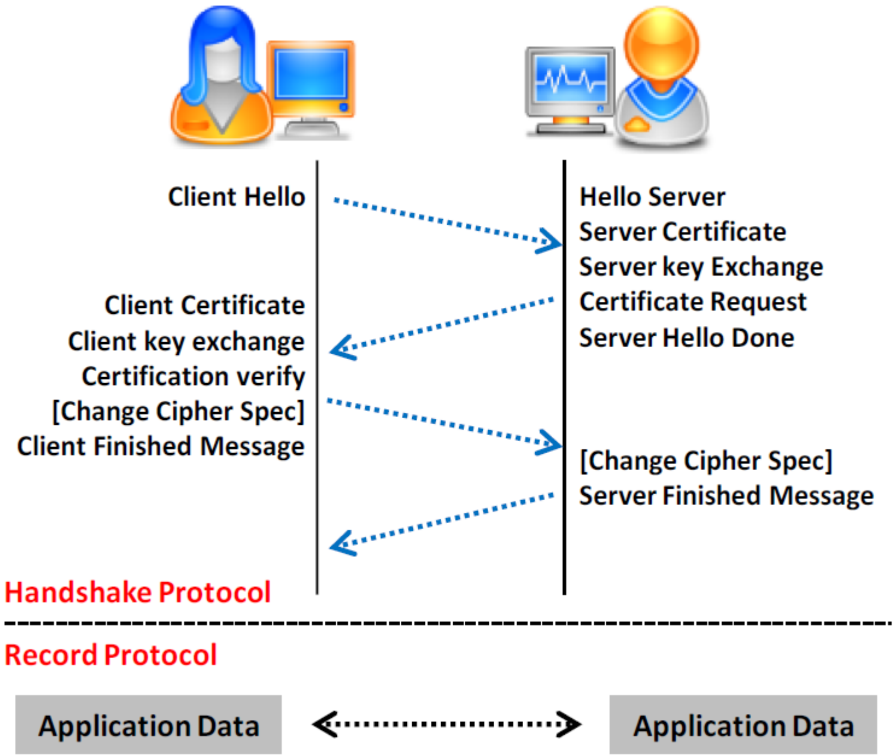
- SSL is an application layer protocol developed by Netscape for managing the security of a message transmission on the Internet.
- It uses RSA asymmetric (public key) encryption to encrypt data transferred over SSL connections.

Encryption Algorithms

Transport Layer Security (TLS)

- TLS is a protocol to establish a secure connection between a client and a server and ensure privacy and integrity and authentication of information during transmission.
- It uses the RSA algorithm with 1024 and 2048 bit strengths.
- **TLS Handshake Protocol**: It allows the client and server to authenticate each other, select encryption algorithm, and exchange symmetric key prior to data exchange.
- **TLS Record Protocol**: It provides secured connections with an encryption method such as Data Encryption Standard (DES).

Encryption Algorithms



10. Pretty Good Privacy (PGP)

Module 19

Encryption Algorithms

- PGP (Pretty Good Privacy) created by Phil Zimmerman, is a protocol used to encrypt and decrypt data that provides authentication and cryptographic privacy.
- PGP is often used for data compression, digital signing, encryption and decryption of messages, emails, files, directories, and to enhance privacy of email communications.
- PGP combines the best features of both conventional and public key cryptography and is therefore known as hybrid cryptosystem.
- PGP and similar software follow the *OpenPGP*, an open standard of PGP encryption software, standard (RFC 4880) for encrypting and decrypting data.

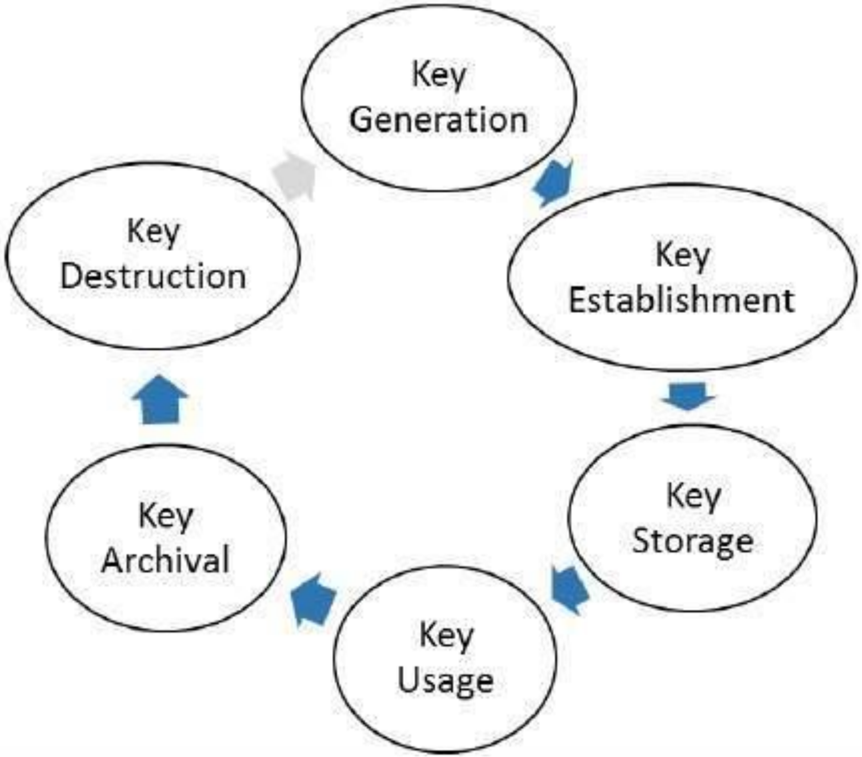
Public Key Infrastructure (PKI)

Module 19

Public Key Infrastructure (PKI)

- The most distinct feature of Public Key Infrastructure (PKI) is that it uses a pair of keys to achieve the underlying security service.
- Since the public keys are in open domain, they are likely to be abused. It is, thus, necessary to establish and maintain some kind of trusted infrastructure to manage these keys.
- **Key Management**
  - Cryptographic keys are nothing but special pieces of data. Key management refers to the secure administration of cryptographic keys.
  - Key management deals with entire key lifecycle.

Public Key Infrastructure (PKI)



Public Key Infrastructure (PKI)

- There are two specific requirements of key management for public key cryptography.
  - **Secrecy of private keys.** Throughout the key lifecycle, secret keys must remain secret from all parties except those who are owner and are authorized to use them.
  - **Assurance of public keys.** In public key cryptography, the public keys are in open domain and seen as public pieces of data. By default there are no assurances of whether a public key is correct, with whom it can be associated, or what it can be used for.

Public Key Infrastructure (PKI)

Public Key Infrastructure (PKI)

- PKI provides assurance of public key. It provides the identification of public keys and their distribution. An anatomy of PKI comprises of the following components.
  - ***Public Key Certificate***, commonly referred to as 'digital certificate'.
  - ***Private Key tokens.***
  - ***Certification Authority.***
  - ***Registration Authority.***
  - ***Certificate Management System.***

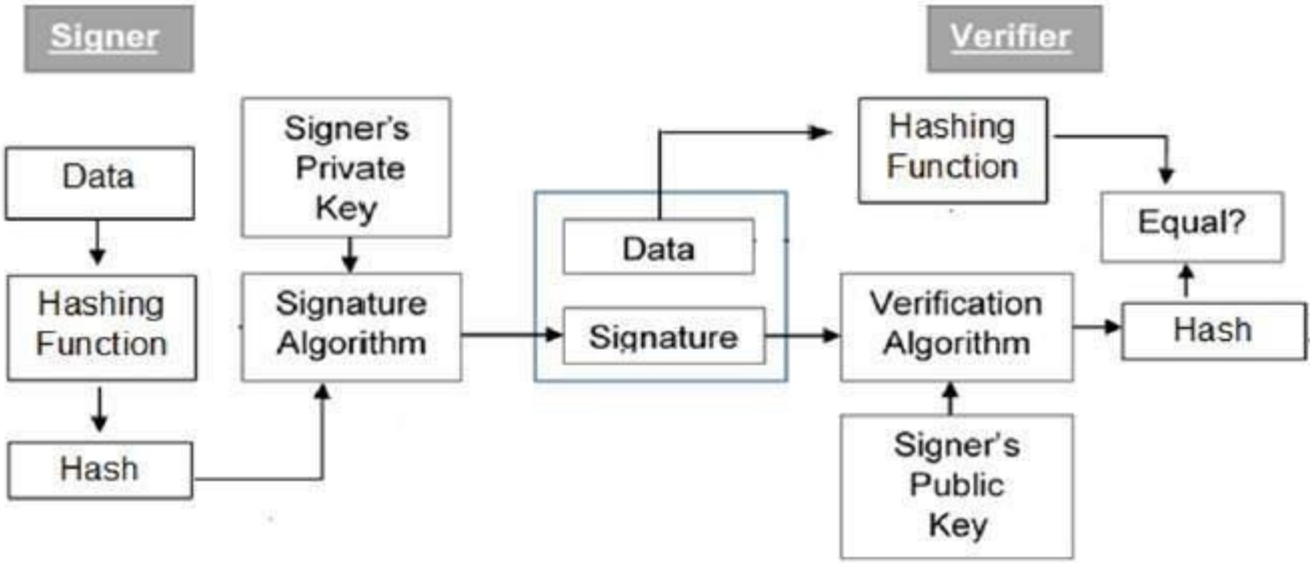
1. Digital Signatures

Module 19

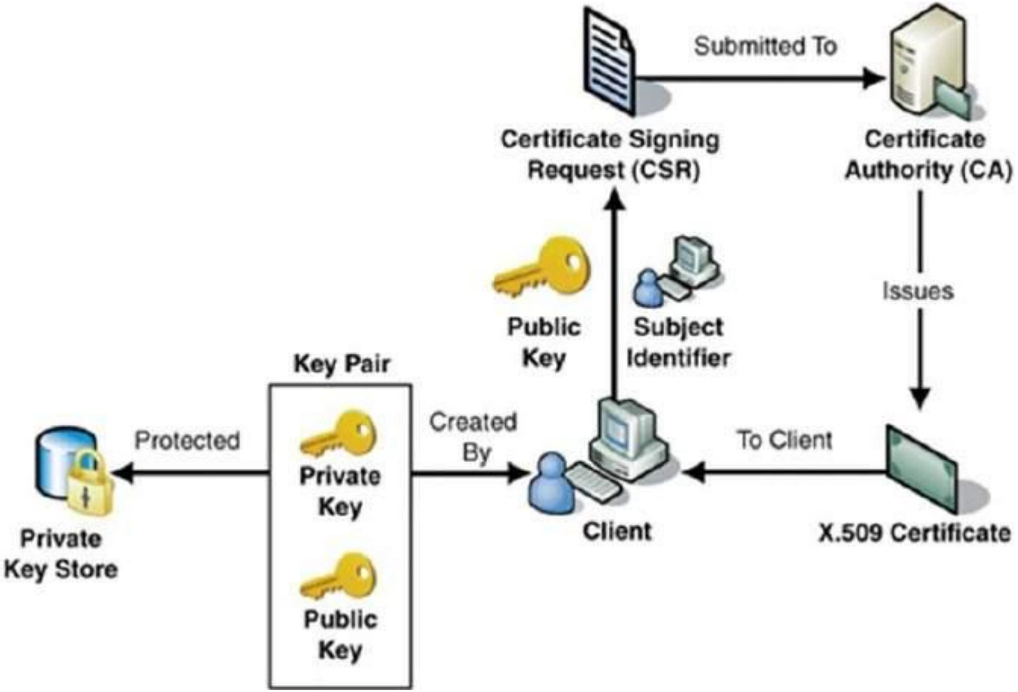
Public Key Infrastructure (PKI)

- **Digital certificates** are based on the ITU standard X.509 which defines a standard certificate format for public key certificates and certification validation.
- Public key pertaining to the user client is stored in digital certificates by The *Certification Authority* (CA) along with other relevant information such as client information, expiration date, usage, issuer etc.
- CA digitally signs this entire information and includes digital signature in the certificate.
- Anyone who needs the assurance about the public key and associated information of client, he carries out the signature validation process using CA's public key. Successful validation assures that the public key given in the certificate belongs to the person whose details are given in the certificate.

Public Key Infrastructure (PKI)



Public Key Infrastructure (PKI)



2. Certification Authorities

Module 19

Public Key Infrastructure (PKI)

- CA issues certificate to a client and assist other users to verify the certificate. The CA takes responsibility for identifying correctly the identity of the client asking for a certificate to be issued, and ensures that the information contained within the certificate is correct and digitally signs it.
- **Key Functions of CA**
  - *Generating key pairs*
  - *Issuing digital certificates*
  - *Publishing Certificates*
  - *Verifying Certificates*
  - *Revocation of Certificates*

Public Key Infrastructure (PKI)

- **Classes of Certificates:** There are four typical classes of certificate –
  - **Class 1** – These certificates can be easily acquired by supplying an email address.
  - **Class 2** – These certificates require additional personal information to be supplied.
  - **Class 3** – These certificates can only be purchased after checks have been made about the requestor’s identity.
  - **Class 4** – They may be used by governments and financial organizations needing very high levels of trust.

Public Key Infrastructure (PKI)

Registration Authority (RA)

- CA may use a third-party Registration Authority (RA) to perform the necessary checks on the person or company requesting the certificate to confirm their identity. The RA may appear to the client as a CA, but they do not actually sign the certificate that is issued.

Certificate Management System (CMS)

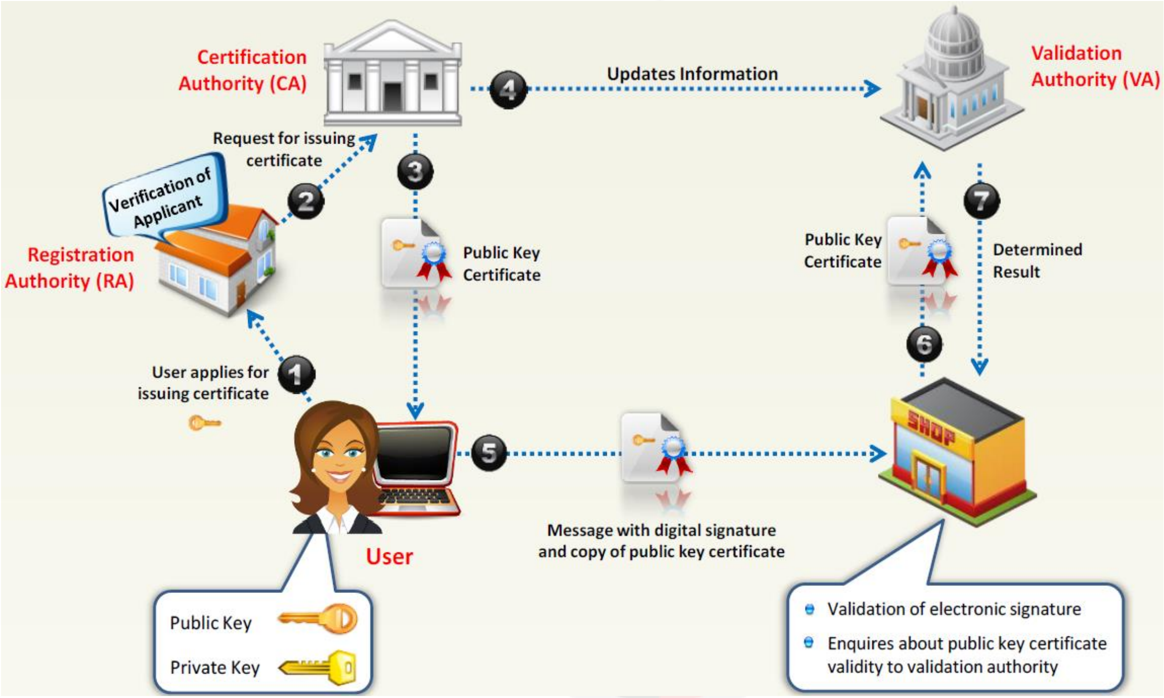
- It is the management system through which certificates are published, temporarily or permanently suspended, renewed, or revoked.

Public Key Infrastructure (PKI)

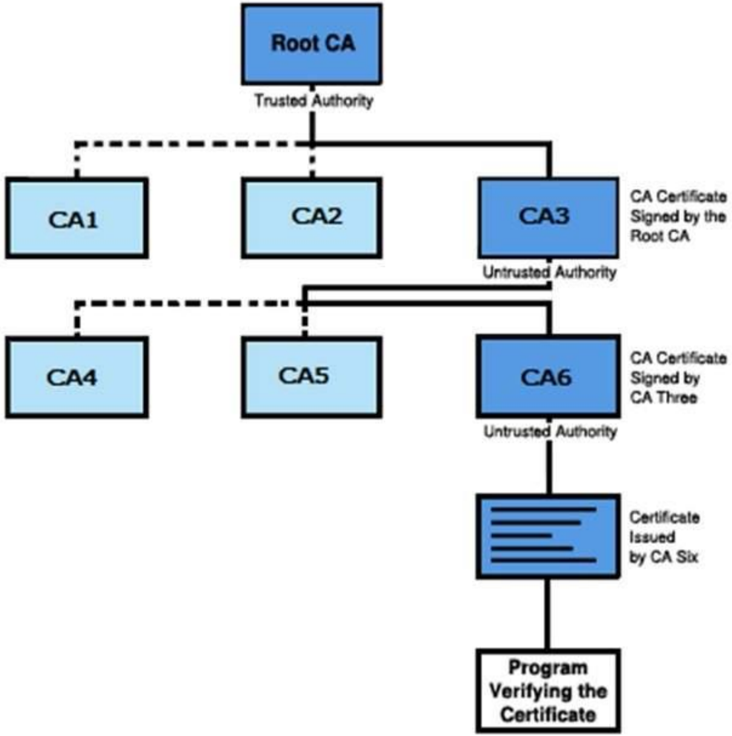
Hierarchy of CA

- It is practically not feasible to have only one trusted CA from whom all users obtain their certificates, also may lead to difficulties if CA is compromised.
- The **root CA** is at the top of the CA hierarchy and the root CA's certificate is a self-signed certificate.
- The CAs, which are directly **subordinate** to the root CA (For example, CA1 and CA2) have CA certificates that are signed by the root CA.
- The CAs under the subordinate CAs in the hierarchy (For example, CA5 and CA6) have their CA certificates signed by the higher-level subordinate CAs.

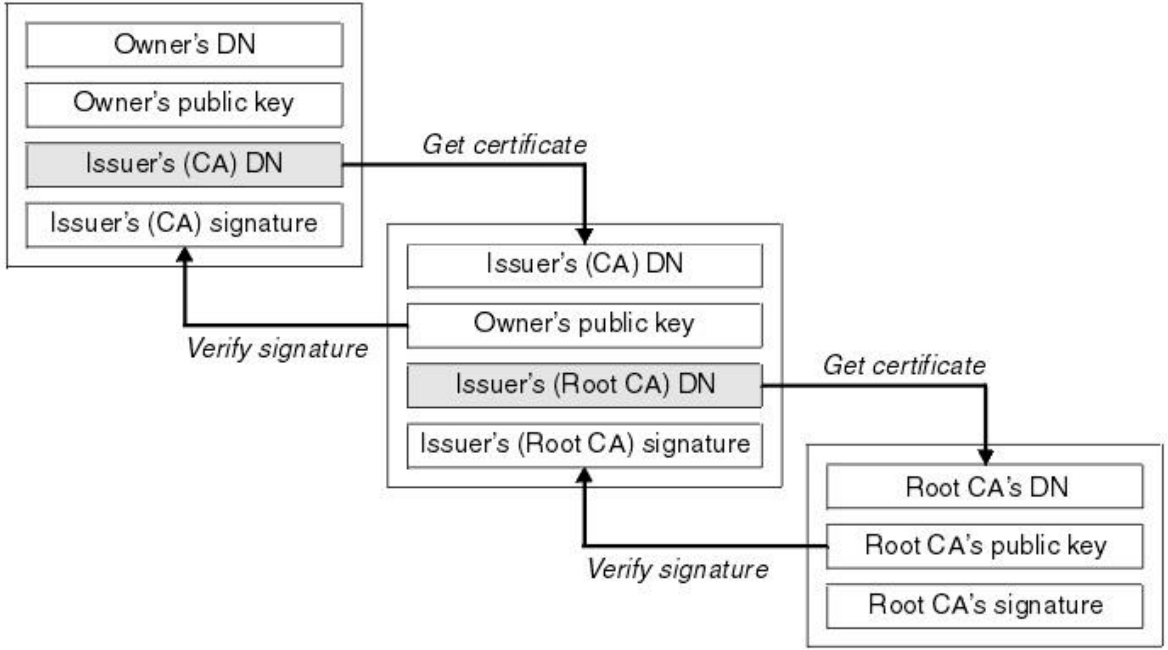
Public Key Infrastructure (PKI)



Public Key Infrastructure (PKI)



Public Key Infrastructure (PKI)



Public Key Infrastructure (PKI)

- A client whose authenticity is being verified supplies his certificate, generally along with the chain of certificates up to Root CA.
- Verifier takes the certificate and validates by using public key of issuer. The issuer's public key is found in the issuer's certificate which is in the chain next to client's certificate.
- Now if the higher CA who has signed the issuer's certificate, is trusted by the verifier, verification is successful and stops here.
- Else, the issuer's certificate is verified in a similar manner as done for client in above steps. This process continues till either trusted CA is found in between or else it continues till Root CA.

Cryptanalysis

Module 19

Cryptanalysis

- Study of analyzing information systems in order to study the hidden aspects of the systems. Cryptanalysis is used to breach cryptographic security systems and gain access to the contents of encrypted messages, even if the cryptographic key is unknown.
- Methods and techniques to reverse the principles of cryptography without knowing the applied algorithms and encryption key.
- Cryptanalysis includes the study of side-channel attacks that do not target weaknesses in the cryptographic algorithms themselves, but instead exploit weaknesses in their implementation.

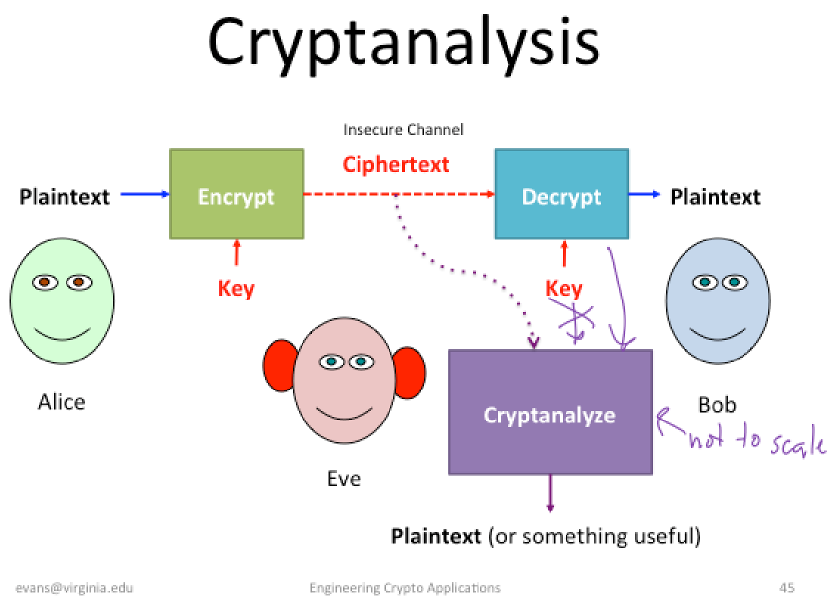
Cryptanalysis

- **Amount of information available to the attacker**
  - *Ciphertext-only*: the cryptanalyst has access only to a collection of ciphertexts or codetexts.
  - *Known-plaintext*: the attacker has a set of ciphertexts to which he knows the corresponding plaintext.
  - *Chosen-plaintext* (*chosen-ciphertext*): the attacker can obtain the ciphertexts (plaintexts) corresponding to an arbitrary set of plaintexts (ciphertexts) of his own choosing.

Cryptanalysis

- **Amount of information available to the attacker**
  - *Adaptive chosen-plaintext*: like a chosen-plaintext attack, except the attacker can choose subsequent plaintexts based on information learned from previous encryptions. Similarly *Adaptive chosen ciphertext attack*.
  - *Related-key attack*: Like a chosen-plaintext attack, except the attacker can obtain ciphertexts encrypted under two different keys. The keys are unknown, but the relationship between them is known; for example, two keys that differ in the one bit.

Cryptanalysis



Cryptanalysis

- Symmetric ciphers
  - Boomerang attack
  - Brute-force attack
  - Davies' attack
  - Differential cryptanalysis
  - Impossible differential cryptanalysis
  - Improbable differential cryptanalysis
  - Integral cryptanalysis

Cryptanalysis

- Linear cryptanalysis
- Meet-in-the-middle attack
- Mod-n cryptanalysis
- Related-key attack
- Sandwich attack
- Slide attack
- XSL attack

Cryptanalysis

- **Attacking cryptographic hash systems**
  - Birthday attack
  - Hash function security summary
  - Rainbow table

Side-channel attack

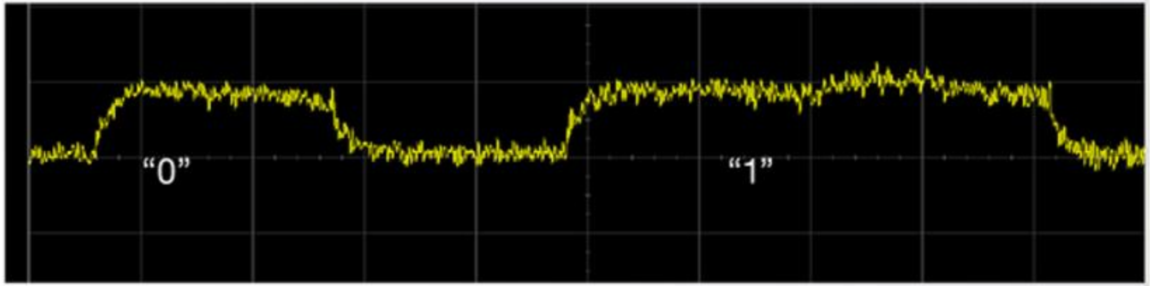
- Attack based on information gained from the implementation of a computer system, rather than weaknesses in the implemented algorithm itself. Timing information, power consumption, electromagnetic leaks or even sound can provide an extra source of information, which can be exploited.
- Some side-channel attacks require technical knowledge of the internal operation of the system, although others such as differential power analysis are effective as black-box attacks.

Cryptanalysis

RSA Timing/Power Attack

$$c = m^e \pmod{n}$$

$$x^n = \begin{cases} x\,(x^2)^{\frac{n-1}{2}}, & \text{if } n \text{ is odd} \\ (x^2)^{\frac{n}{2}}, & \text{if } n \text{ is even.} \end{cases}$$



Cryptanalysis

General

- **Cache attack** — attacks based on attacker's ability to monitor cache accesses made by the victim in a shared physical system as in virtualized environment or a type of cloud service. (***Meltdown*** and ***Spectre*** in 2017)
- **Timing attack** — attacks based on measuring how much time various computations (such as, say, comparing an attacker's given password with the victim's unknown one) take to perform.
- **Power-monitoring attack** — attacks that make use of varying power consumption by the hardware during computation.

Cryptanalysis

- **Electromagnetic attack** — attacks based on leaked electromagnetic radiation, which can directly provide plaintexts and other information. Such measurements can be used to infer cryptographic keys using techniques equivalent to those in power analysis or can be used in non-cryptographic attacks, e.g. *TEMPEST* (aka ***van Eck phreaking*** or ***radiation monitoring***) attacks.
- **Acoustic cryptanalysis** — attacks that exploit sound produced during a computation (rather like power analysis).
- **Differential fault analysis** — in which secrets are discovered by introducing faults in a computation.

Cryptanalysis

- **Data remanence** — in which sensitive data are read after supposedly having been deleted. (i.e. *Cold boot attack*)
- **Software-initiated fault attacks** — Currently a rare class of side-channels, *Row hammer* is an example in which off-limits memory can be changed by accessing adjacent memory too often (causing state retention loss).
- **Optical** - in which secrets and sensitive data can be read by visual recording using a high resolution camera, or other devices that have such capabilities.

HACKING

Is an art, practised through a creative mind.