Unit 1:services and mechanisms

Ref:Cryptography and Network Security Principles and Practice, 5th Edition by William Stallings

OSI(Open system interconnection) ARCHITECTURE

- Security Attack
- Security Service
- Security Mechanism

Security Services

- **Authentication**
  - Peer Entity Authentication: sender & receiver
  - Data origin Authentication: source
- **Access Control**:not for unauthorized user
- **Data Confidentiality**
  - Connection Confidentiality: all user data
  - Connectionless Confidentiality: all user data in a single block
  - Selective field Confidentiality :selected field
  - Traffic Flow Confidentiality: based on observation of traffic flow

Contd..

- **Data Integrity**
  - Connection integrity with recovery: detection and recovery
  - Connection integrity without recovery: only detection
  - Selective field connection integrity
  - Connectionless Integrity
  - Selective field connectionless integrity
- **NonRepudiation**
  - Non Repudiation, Origin
  - Non Repudiation, Destination

Security Mechanisms

- Specific Security Mechanisms: for a particular layer
  - Encipherment
  - Data Integrity
  - Digital Signature
  - Authentication Exchange
  - Traffic Padding
  - Routing Control
  - Notarization
  - Access Control

- Pervasive Security Mechanism: Not specific to a layer
  - Trusted Functionality
  - Security label
  - Event Detection
  - Security Audit trail
  - Security Recovery

Classical Encryption Techniques

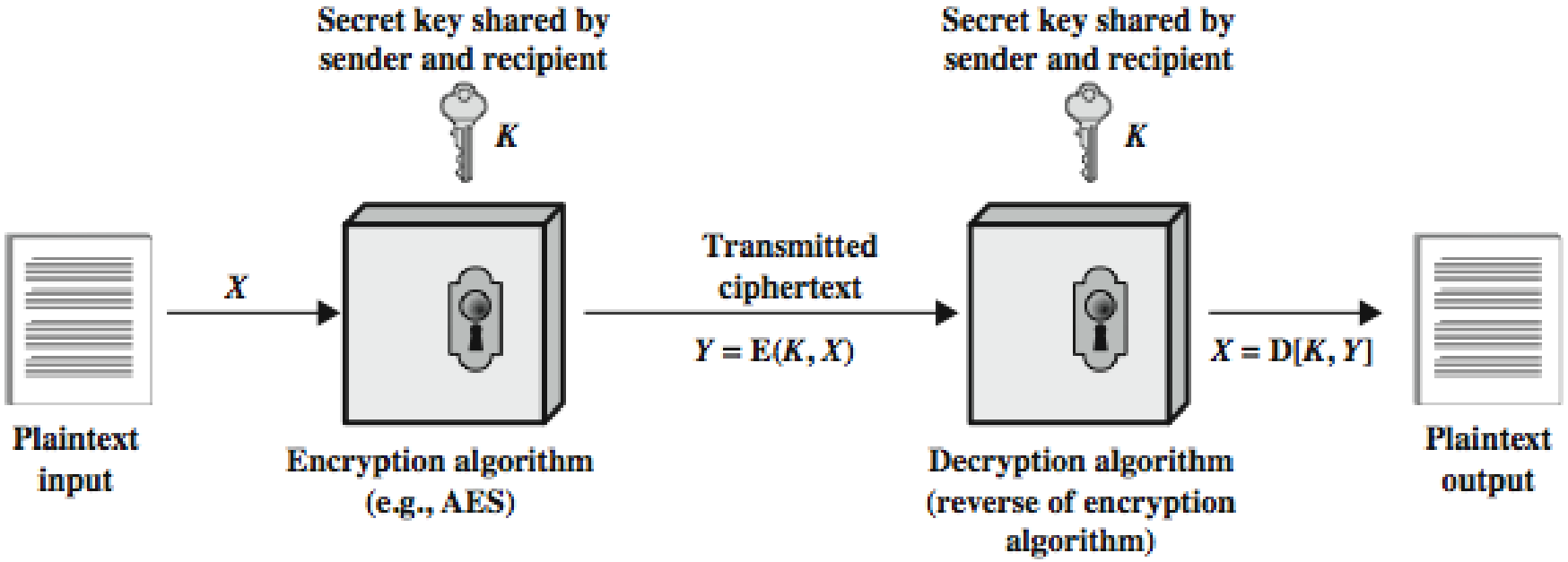
Ref:Cryptography and Network Security Principles and Practice, 5th Edition by William Stallings

Basic Terminology

- **plaintext** - original message
- **ciphertext** - coded message
- **cipher** - algorithm for transforming plaintext to ciphertext
- **key** - info used in cipher known only to sender/receiver
- **cryptography** - study of encryption principles/methods
- **cryptanalysis (codebreaking)** - study of principles/ methods of deciphering ciphertext *without* knowing key
- **cryptology** - field of both cryptography and cryptanalysis

- **Encryption** is the process of translating plain text data (plaintext) into something that appears to be random and meaningless (cipher text).
- **Decryption** is the process of converting cipher text back to plaintext. To **encrypt** more than a small amount of data, symmetric **encryption** is used.
- **Symmetric Encryption** or conventional / private-key / single-key
- sender and recipient share a common key
- all classical encryption algorithms are private-key.

Symmetric Cipher Model



Requirements

- two requirements for secure use of symmetric encryption:
  - a strong encryption algorithm
  - a secret key known only to sender / receiver
- mathematically have:

  $Y = E(K, X)$

  $X = D(K, Y)$
- assume encryption algorithm is known
- implies a secure channel to distribute key

Cryptography

- can characterize cryptographic system by:
  - type of encryption operations used
    - substitution
    - transposition
    - product
  - number of keys used
    - single-key or private
    - two-key or public
  - way in which plaintext is processed
    - block
    - stream

Cryptanalysis

- objective to recover key not just message
- general approaches:
  - cryptanalytic attack
  - brute-force attack
- if either succeed all key used are compromised

Kerckhoff's principle

- The concept that a Cryptographic system should be designed to be secure, even if all its details, except for the key, are publicly known.

Cryptanalytic Attacks

Type of Attack	Known to Cryptanalyst
Ciphertext Only	• Encryption algorithm • Ciphertext
Known Plaintext	• Encryption algorithm • Ciphertext • One or more plaintext–ciphertext pairs formed with the secret key
Chosen Plaintext	• Encryption algorithm • Ciphertext • Plaintext message chosen by cryptanalyst, together with its corresponding ciphertext generated with the secret key
Chosen Ciphertext	• Encryption algorithm • Ciphertext • Ciphertext chosen by cryptanalyst, together with its corresponding decrypted plaintext generated with the secret key
Chosen Text	• Encryption algorithm • Ciphertext • Plaintext message chosen by cryptanalyst, together with its corresponding ciphertext generated with the secret key • Ciphertext chosen by cryptanalyst, together with its corresponding decrypted plaintext generated with the secret key

Definitions

- **unconditional security**
  - no matter how much computer power or time is available, the cipher cannot be broken since the ciphertext provides insufficient information to uniquely determine the corresponding plaintext
- **computational security**
  - Given limited computing resources (eg time needed for calculations is greater than age of universe), the cipher cannot be broken .

Brute Force Search

- always possible to simply try every key
- most basic attack, proportional to key size
- assume either know / recognise plaintext

Key Size (bits)	Number of Alternative Keys	Time required at 1 decryption/μs	Time required at 10^6 decryptions/μs
32	$2^{32} = 4.3 \times 10^9$	2^{31} μs = 35.8 minutes	2.15 milliseconds
56	$2^{56} = 7.2 \times 10^{16}$	2^{55} μs = 1142 years	10.01 hours
128	$2^{128} = 3.4 \times 10^{38}$	2^{127} μs = 5.4×10^{24} years	5.4×10^{18} years
168	$2^{168} = 3.7 \times 10^{50}$	2^{167} μs = 5.9×10^{36} years	5.9×10^{30} years
26 characters (permutation)	$26! = 4 \times 10^{26}$	2×10^{26} μs = 6.4×10^{12} years	6.4×10^6 years

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Classical Substitution Ciphers

- where letters of plaintext are replaced by other letters or by numbers or symbols
- or if plaintext is viewed as a sequence of bits, then substitution involves replacing plaintext bit patterns with ciphertext bit patterns

Caesar Cipher

- earliest known substitution cipher
- by Julius Caesar
- It is a type of substitution cipher in which each letter in the plaintext is replaced by a letter some fixed number of positions down the alphabet.
- first attested use in military affairs

- replaces each letter by 3rd letter on
- example:

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

Encode the word "spongebob" with a Caesar cipher with a forward shift of 11.

Caesar Cipher

- can define transformation as:

```
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
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
```

- mathematically give each letter a number

Eg., Plain text is E G G
Cipher text is H J J since key is 3

- Then have Caesar cipher as:

$c = E(k, p) = (p + k) \bmod (26)$ **=(4+5) mod 26=9(J)**

$p = D(k, c) = (c - k) \bmod (26)$ **=(9-5) mod 26=4(E)**

Cryptanalysis of Caesar Cipher

- only have 26 possible ciphers
  - A maps to A,B,..Z
- could simply try each in turn
- a **brute force search**
- given ciphertext, just try all shifts of letters
- eg. break ciphertext "GCUA VQ DTGCM"

Monoalphabetic Cipher

- rather than just shifting the alphabet
- could shuffle (jumble) the letters arbitrarily
- each plaintext letter maps to a different random ciphertext letter
- hence key is 26 letters long

```
Plain:    a bcd e fghI jklmnopqrstuvwxyz
Cipher: DKVQFIBJWPESCXHTMYAUOLRGZN

Plaintext:  ifwewishtoreplaceletters
Ciphertext: WIRFRWAJUHYFTSDVFSFUUFYA
```

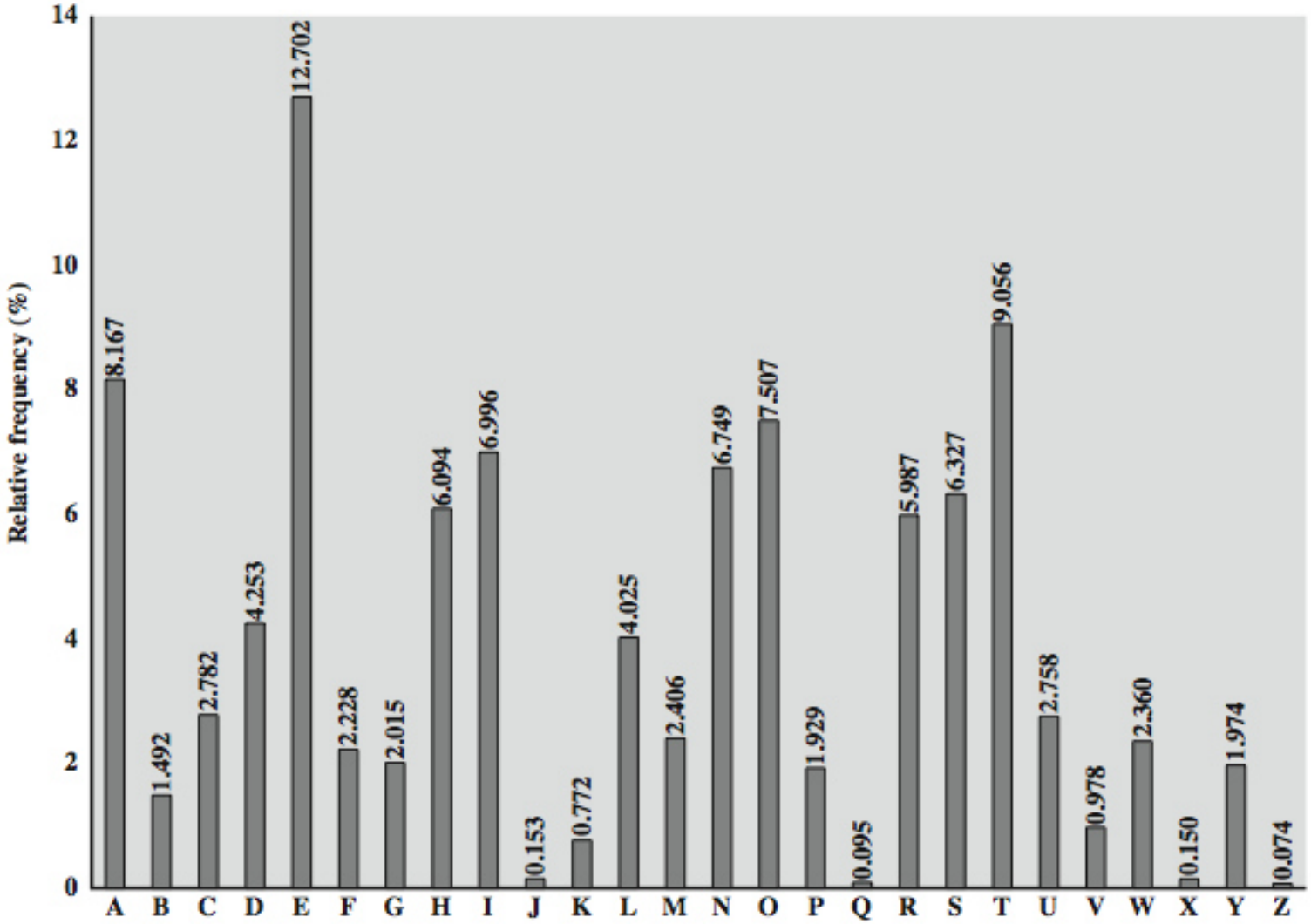
Monoalphabetic Cipher Security

- now have a total of 26! = 4 x 10^{26} keys
- with so many keys, might think is secure
- but would be **!!!WRONG!!!**
- problem is language characteristics

Language Redundancy and Cryptanalysis

- human languages are **redundant**
- eg "th lrd s m shphrd shll nt wnt"
- letters are not equally commonly used
- in English E is by far the most common letter
  - followed by T,R,N,I,O,A,S
- other letters like Z,J,K,Q,X are fairly rare
- have tables of single, double & triple letter frequencies for various languages

English Letter Frequencies



Use in Cryptanalysis

- key concept - monoalphabetic substitution ciphers do not change relative letter frequencies
- discovered by Arabian scientists in 9th century
- calculate letter frequencies for ciphertext
- compare counts/plots against known values
- if caesar cipher look for common peaks/troughs
  - peaks at: A-E-I triple, NO pair, RST triple
  - troughs at: JK, X-Z
- for monoalphabetic must identify each letter
  - tables of common double/triple letters help

Example Cryptanalysis

- given ciphertext:

  UZQSOVUOHXMOPVGPOZPEVSGZWSZOPFPESXUDBMETSXAIZ
  VUEPHZHMDZSHZOWSFPAPPDTSVPQUZWYMXUZUHSX
  EPYEPOPDZSZUFPOMBZWPFUPZHMDJUDTMOHMQ

- count relative letter frequencies (see text)
- guess P & Z are e and t
- guess ZW is th and hence ZWP is the
- proceeding with trial and error finally get:

  it was disclosed yesterday that several informal but
  direct contacts have been made with political
  representatives of the viet cong in moscow

Playfair Cipher

Ref : AtulKahate , Cryptography and Network Security,Tata McGraw Hill,2003

Playfair Cipher

- Not even the large number of keys in a monoalphabetic cipher provides security
- One approach to improving security is to encrypt multiple letters
- **Playfair Cipher** is an example.
- It was invented by Charles Wheatstone in 1854, but named after his friend Baron Playfair

Playfair Key Matrix

- a 5X5 matrix of letters based on a keyword
- fill in letters of keyword
- fill rest of matrix with other letters
- eg. using the keyword MONARCHY

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

Encrypting and Decrypting

- plaintext is encrypted two letters at a time
  1. if a pair is a repeated letter, insert filler like 'X'

     For Example if the plain text is **BALLOON** has to be encrypted , it should be separated and grouped as pair. I**t can be written as**

     BA/LX/LO/ON ------→ Filler

     If characters in plain text are repeated then they are grouped with the help of filler.

2. if both letters fall in the same row, replace each with letter to right (wrapping back to start from end)

3. if both letters fall in the same column, replace each with the letter below it (wrapping to top from bottom)

4. otherwise each letter is replaced by the letter in the same row and in the column of the other letter of the pair

Eg., Using the keyword **MONARCHY** encrypt the following text

AR --→ RM

CL --→ EU

FW --→GV

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

Security of Playfair Cipher

- security much improved over monoalphabetic
- since have 26 x 26 = 676 digrams
- would need a 676 entry frequency table to analyse (verses 26 for a monoalphabetic)
- and correspondingly more ciphertext
- was widely used for many years
  - eg. by US & British military in WW1
- it **can** be broken, given a few hundred letters since still has much of plaintext structure

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Polyalphabetic Ciphers

- **polyalphabetic substitution ciphers**
- improve security using multiple cipher alphabets
- make cryptanalysis harder with more alphabets to guess and flatter frequency distribution
- use a key to select which alphabet is used for each letter of the message
- use each alphabet in turn
- repeat from start after end of key is reached

Example:Vigenère Cipher

- simplest polyalphabetic substitution cipher
- effectively multiple caesar ciphers
- key is multiple letters long $K = k_1\ k_2\ \ldots\ k_d$
- i^{th} letter specifies i^{th} alphabet to use

  use each alphabet in turn
- repeat from start after d letters in message
- decryption simply works in reverse

Example of Vigenère Cipher

- write the plaintext out
- write the keyword repeated above it
- use each key letter as a caesar cipher key
- encrypt the corresponding plaintext letter
- eg using keyword *deceptive*

K	d	e	c	e	p	t	i	v	e	d	e	c	e	p	t	i	v	e	d	e	c	e	p	t	i	v	e
p	w	e	a	r	e	d	i	s	c	o	v	e	r	e	d	s	a	v	e	y	o	u	r	s	e	l	f

ciphertext: **Z**IC**VTW**QNGRZG**VTW**AVZHCQYGLMGJ

- length of the key is 3 or 9 based on the displacement of “VTW”

Vignere tableau

	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

Autokey Cipher

- ideally want a key as long as the message
- Vigenère proposed the **autokey** cipher
- with keyword is prefixed to message as key
- knowing keyword can recover the first few letters
- use these in turn on the rest of the message

- but still have frequency characteristics to attack

key:deceptivewearediscoveredsav

plaintext:wearediscoveredsaveyourself

ciphertext:ZICVTWQNGKZEIIGASXSTSLVVWLA

Vernam Cipher

- ultimate defense is to use a key as long as the plaintext
- with no statistical relationship to it
- invented by AT&T engineer Gilbert Vernam in 1918
- originally proposed using a very long but eventually repeating key
- Works on binary numbers rather than letters

One-Time Pad

- if a truly random key as long as the message is used, the cipher will be secure
- called a One-Time pad
- is unbreakable since ciphertext bears no statistical relationship to the plaintext
- since for **any plaintext** & **any ciphertext** there exists a key mapping one to other
- can only use the key **once** though
- problems in generation & safe distribution of key

- Cipher text:ANKYODKYURYREYTPLUYFCBA
- Key:PXLMVMSSYDOJDSPLREYIUN
- Plain Text : MISS SCARLET WITH THE KNIFE

- Cipher text:ANKYODKYURYREYTPLUYFCBA
- Key:OFDOIUERFPLUYTZJIOQIDLE
- Plain text:Mr Mustard with the candle

Transposition Ciphers

Ref:Cryptography and Network Security Principles and Practice, 5th Edition by William Stallings

Transposition Ciphers

- Consider classical **transposition** or **permutation** ciphers
- These hide the message by rearranging the order of letter
- Without altering the actual letters used
- Can be recognised these since they have the same frequency distribution as the original text

Rail Fence cipher

- write message letters out diagonally over a number of rows
- then read off cipher row by row
- eg. **MEET ME AFTER THE TOGA PARTY**
- write message out as:

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

- giving ciphertext

```
MEMATRHTGPRYETEFETEOAAT
```

Row Transposition Ciphers

- is a more complex transposition
- write letters of message out in rows over a specified number of columns
- then reorder the columns according to some key before reading off the rows
- **Eg.,attack postponed until two am**

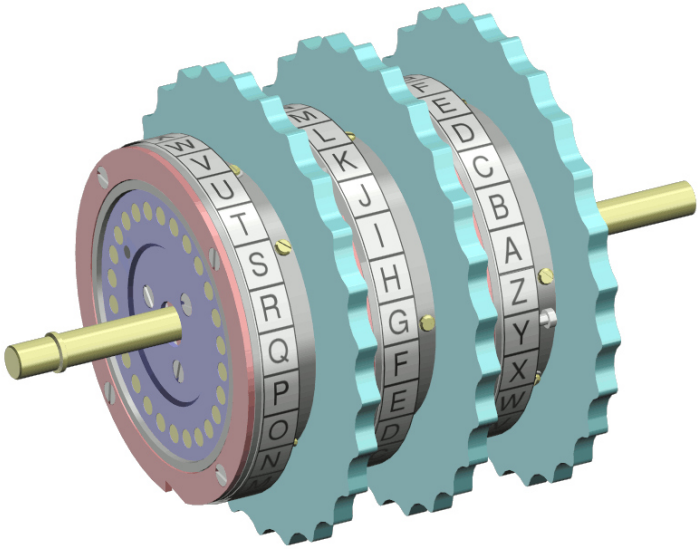
```
Key: 4312567
Column Out     4   3   1   2  5  6  7
Plaintext   :      a   t   t  a  c  k  p
                   o   s   t  p  o  n  e
                   d   u   n  t  i  l  t
                   w   o   a  m  x  y  z
Ciphertext: TTNAAPTMTSUOAODWCOIXKNLYPETZ
```

Product Ciphers

- ciphers using substitutions or transpositions are not secure because of language characteristics
- hence consider using several ciphers in succession to make harder, but:
  - two substitutions make a more complex substitution
  - two transpositions make more complex transposition
  - but a substitution followed by a transposition makes a new much harder cipher
- this is to bridge from classical to modern ciphers

Rotor Machines

- before modern ciphers, rotor machines were most common complex ciphers in use
- widely used in WW2
  - German Enigma, Allied Hagelin, Japanese Purple
- implemented a very complex, varying substitution cipher
- used a series of cylinders, each giving one substitution, which rotated and changed after each letter was encrypted
- with 3 cylinders have $26^3=17576$ different substitution alphabets



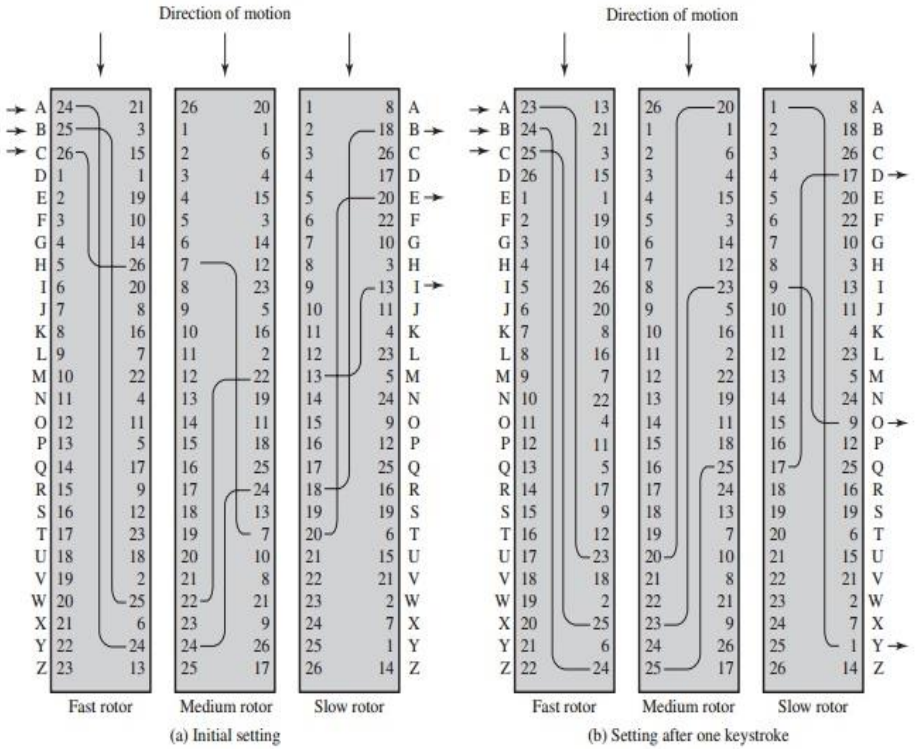


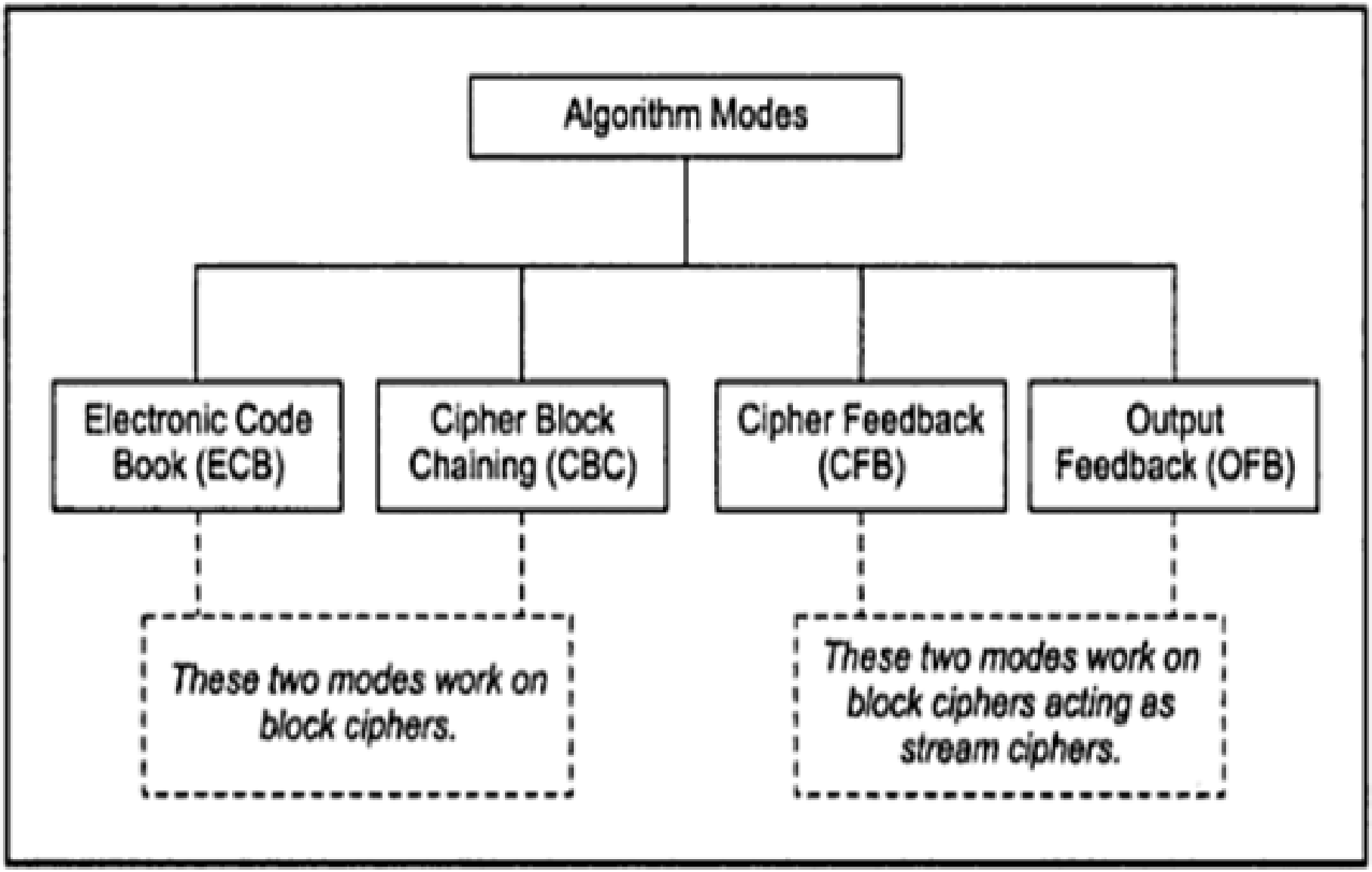
Figure 2.8 Three-Rotor Machine with Wiring Represented by Numbered Contacts

Steganography

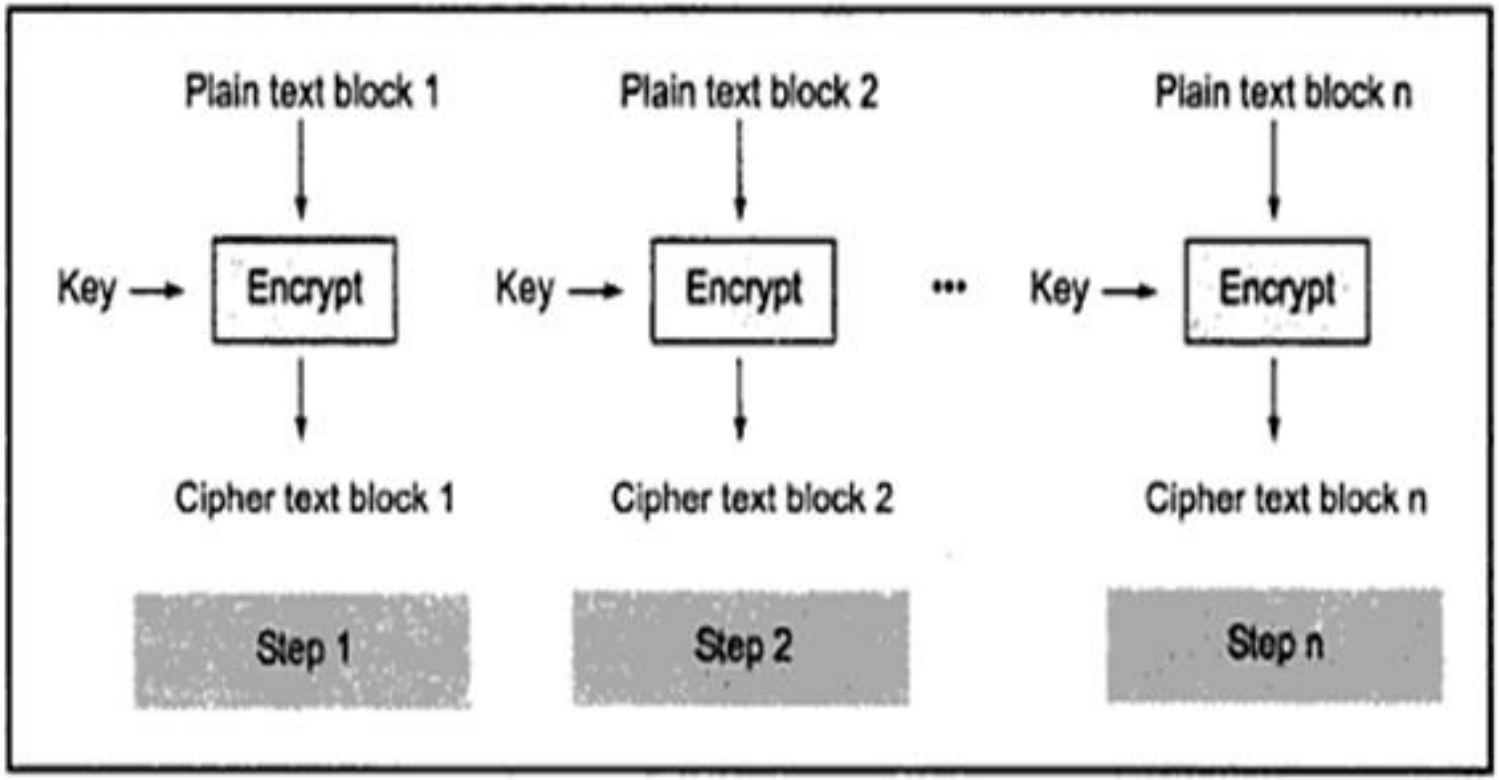
- an alternative to encryption
- hides existence of message
  - using only a subset of letters/words in a longer message marked in some way
  - using invisible ink
  - hiding in LSB in graphic image or sound file
- has drawbacks
  - high overhead to hide relatively few info bits
- advantage is can obscure encryption use

Modes of Operation

Ref:Cryptography and Network Security-Atul Kahate

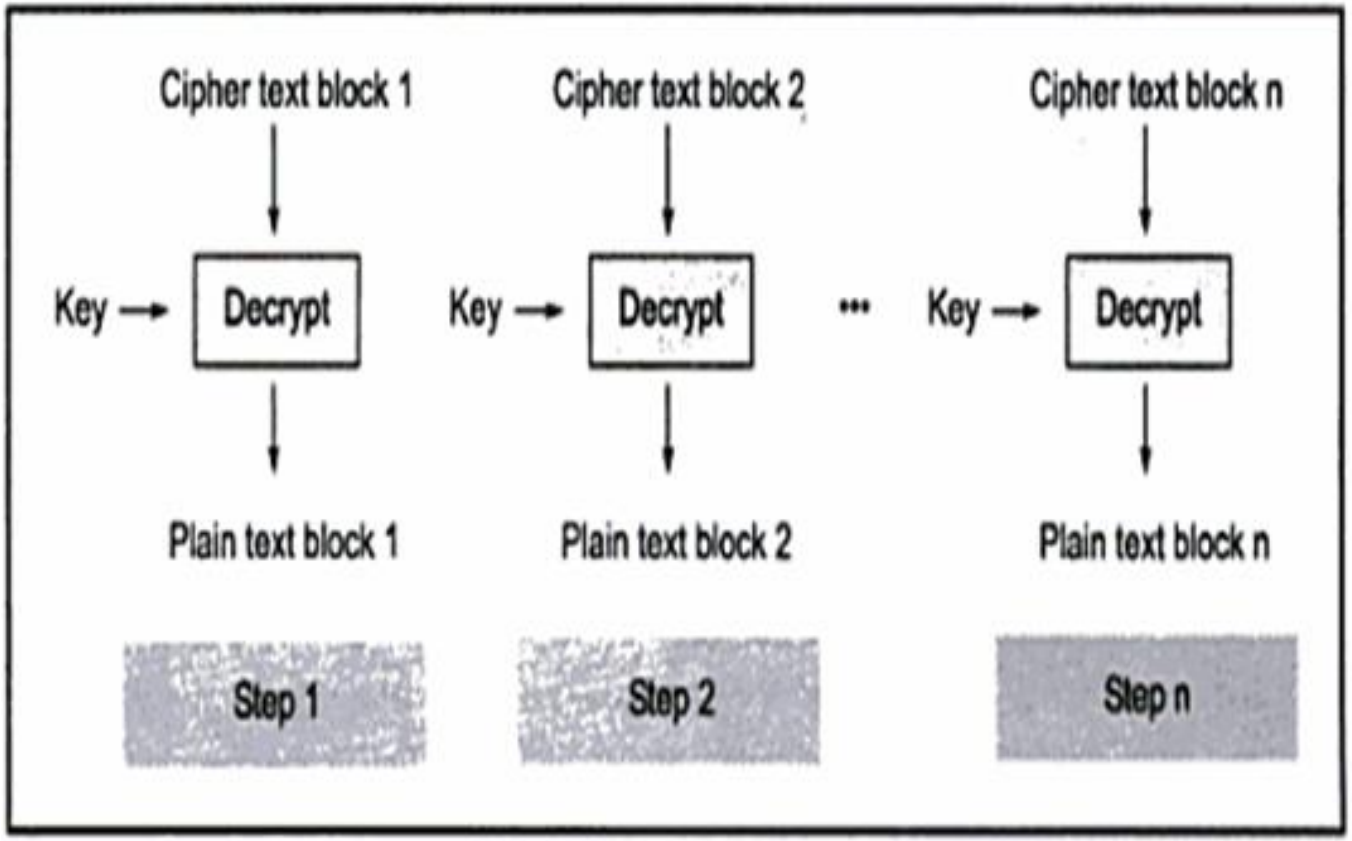

Algorithm Modes
Electronic Code Book (ECB)
Cipher Block Chaining (CBC)
Cipher Feedback (CFB)
Output Feedback (OFB)
These two modes work on block ciphers.
These two modes work on block ciphers acting as stream ciphers.

Electronic Code Book(ECB)



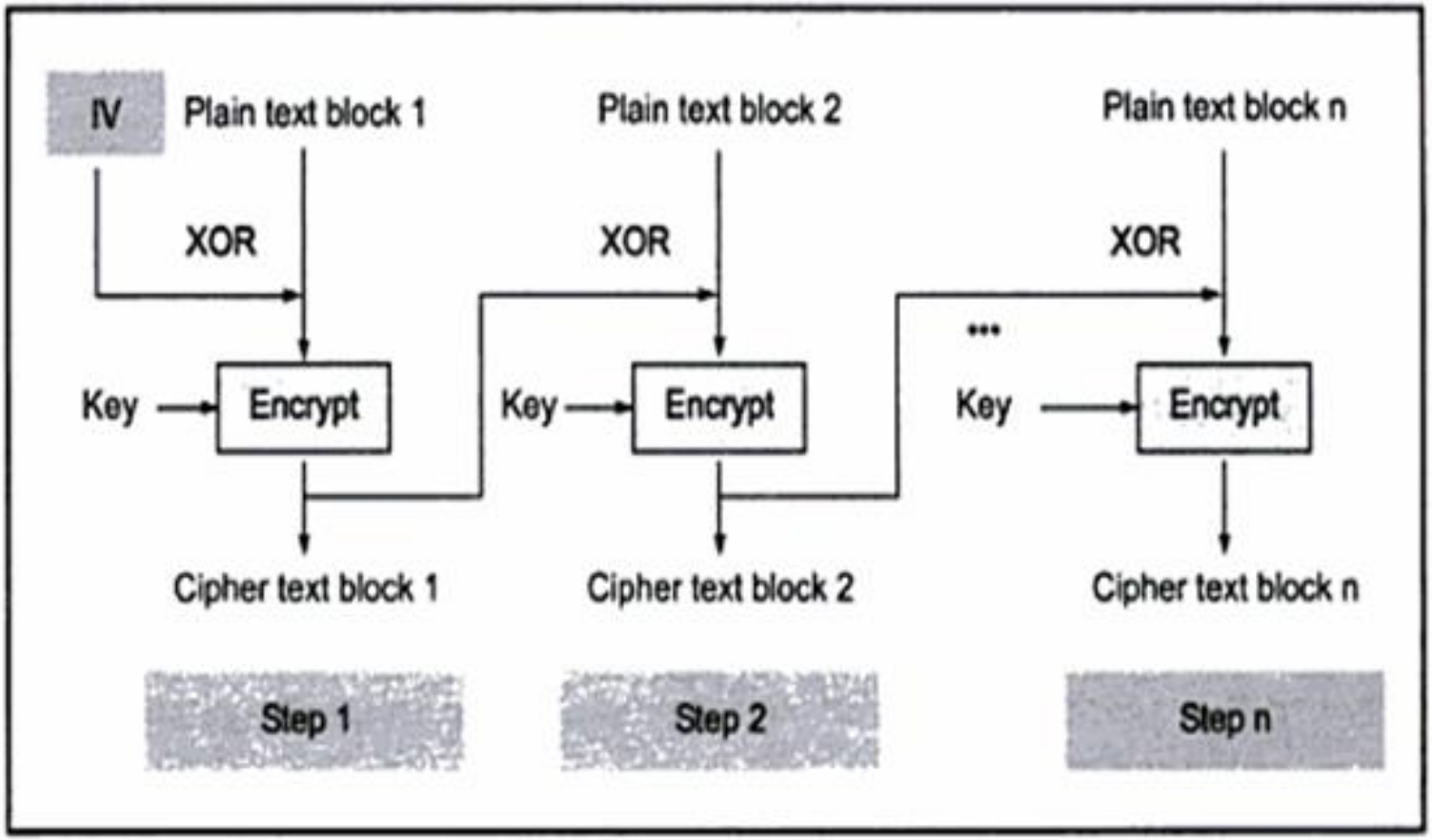
ECB mode – The encryption process

Decryption Process

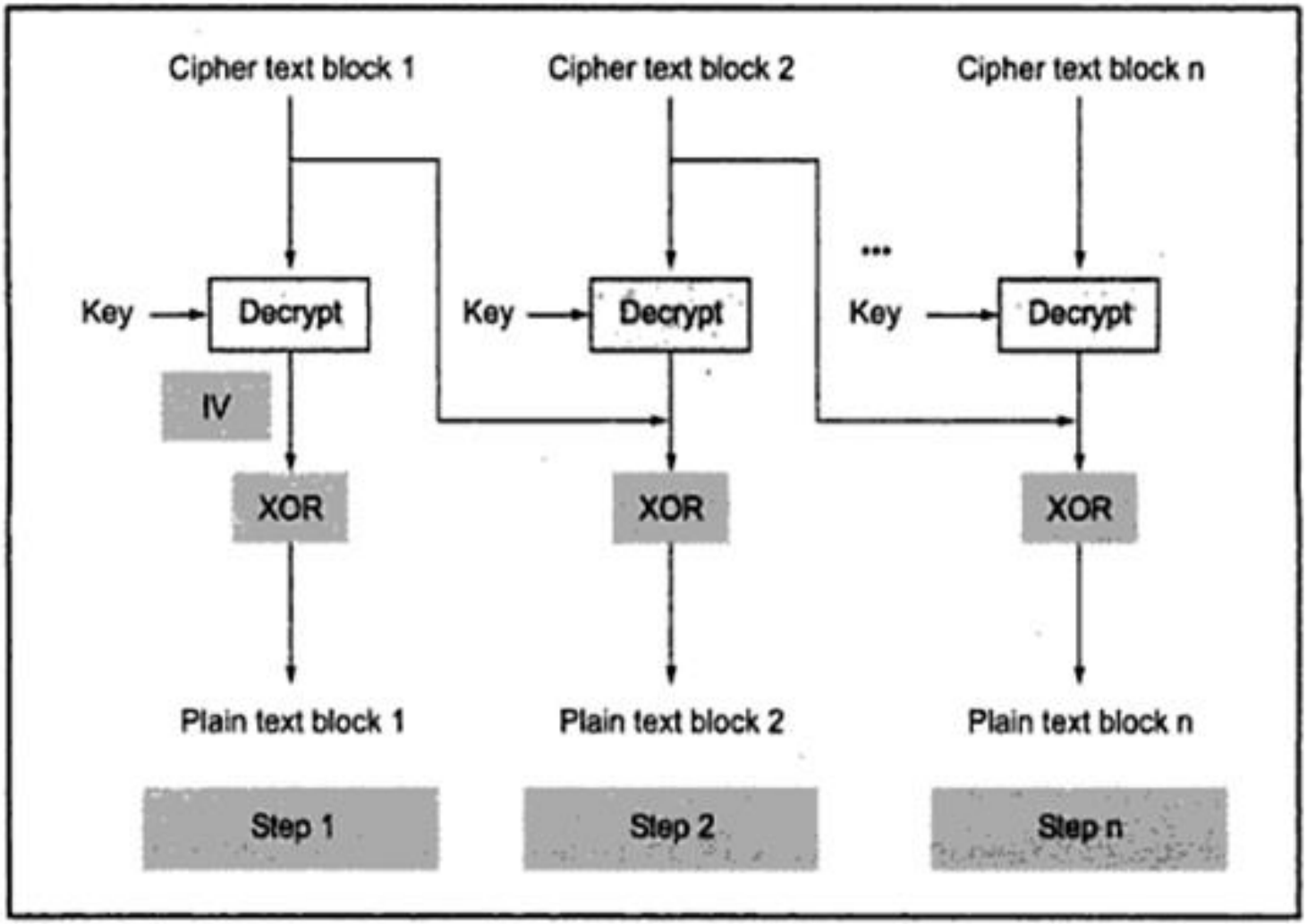


ECB mode – The decryption process

Cipher Block chaining(CBC) Mode

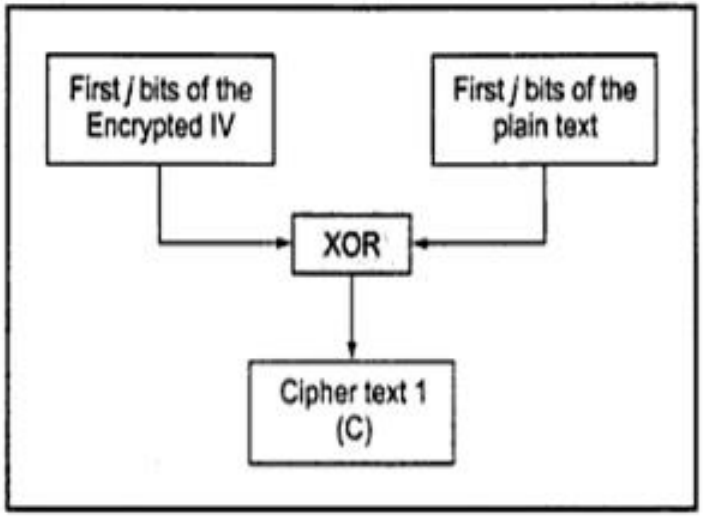


CBC mode – The encryption process

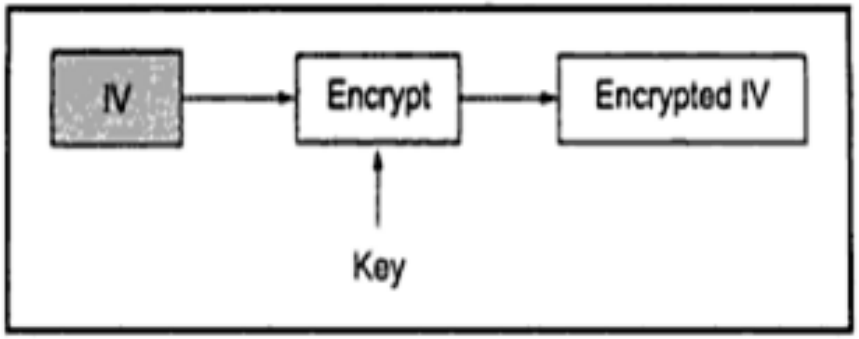


CBC mode – The decryption process

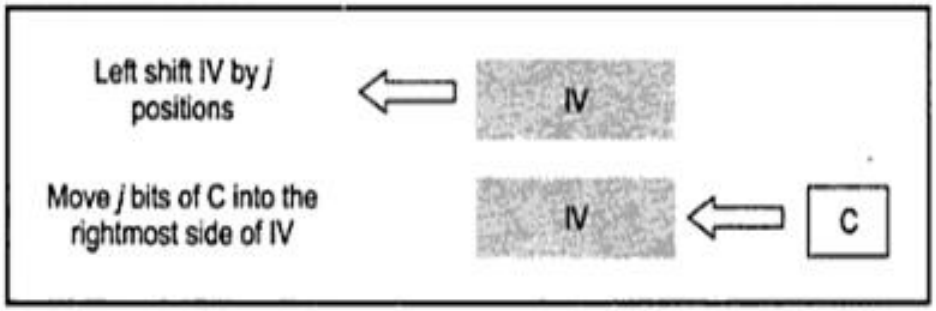
Cipher Feedback (CFB) Mode



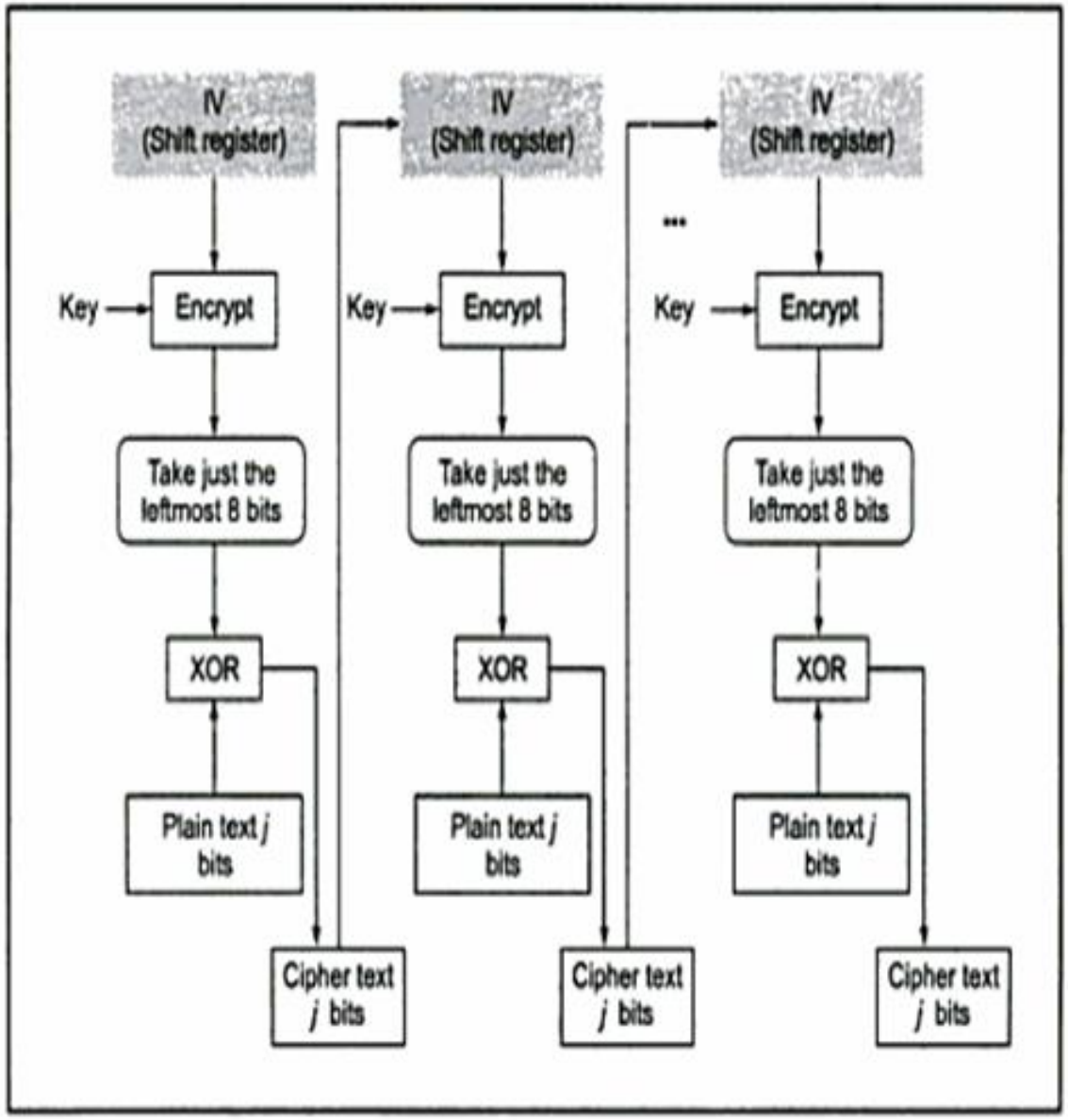
CFB – Step 2



CFB – Step 1

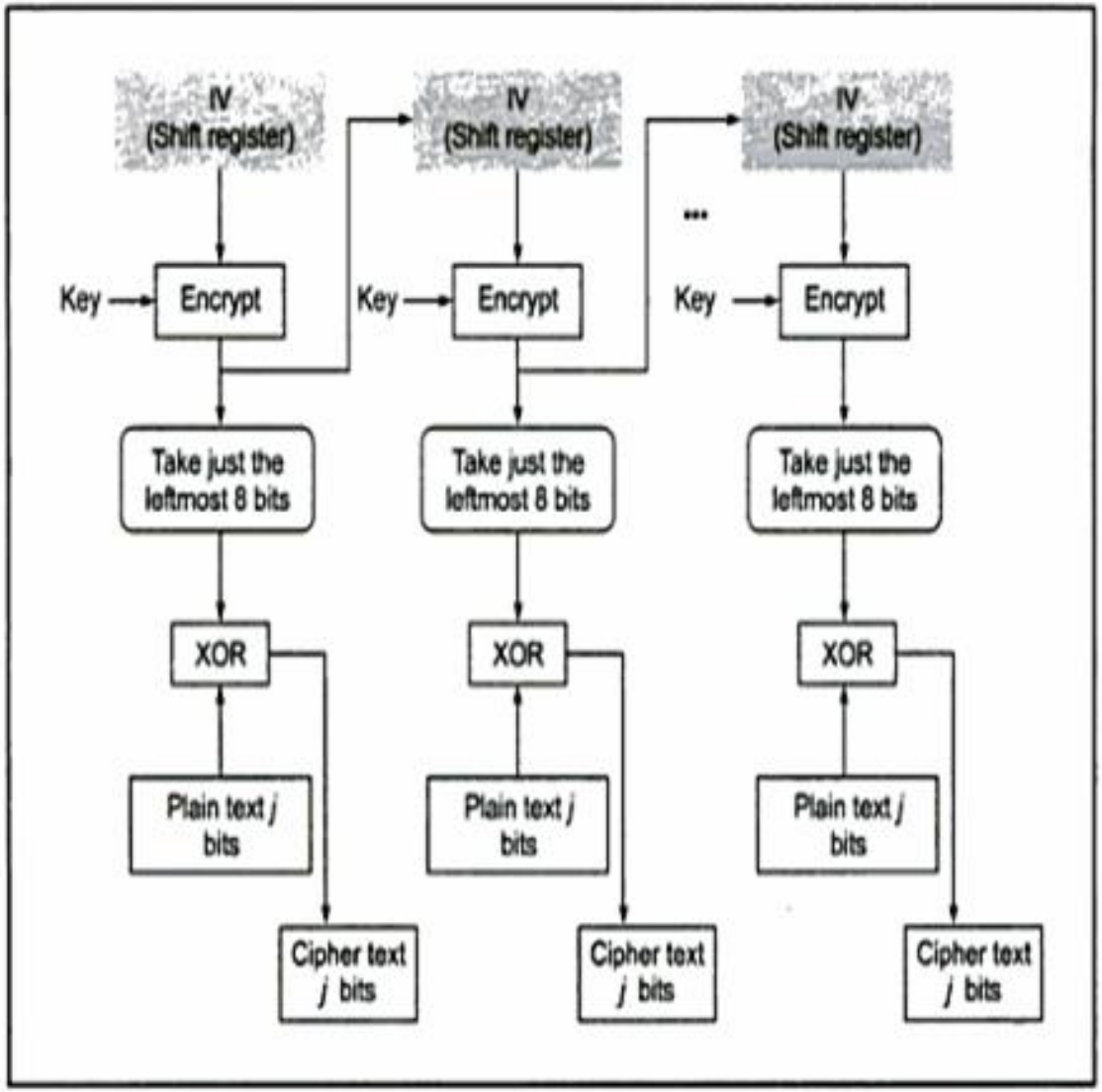


CFB – Step 3



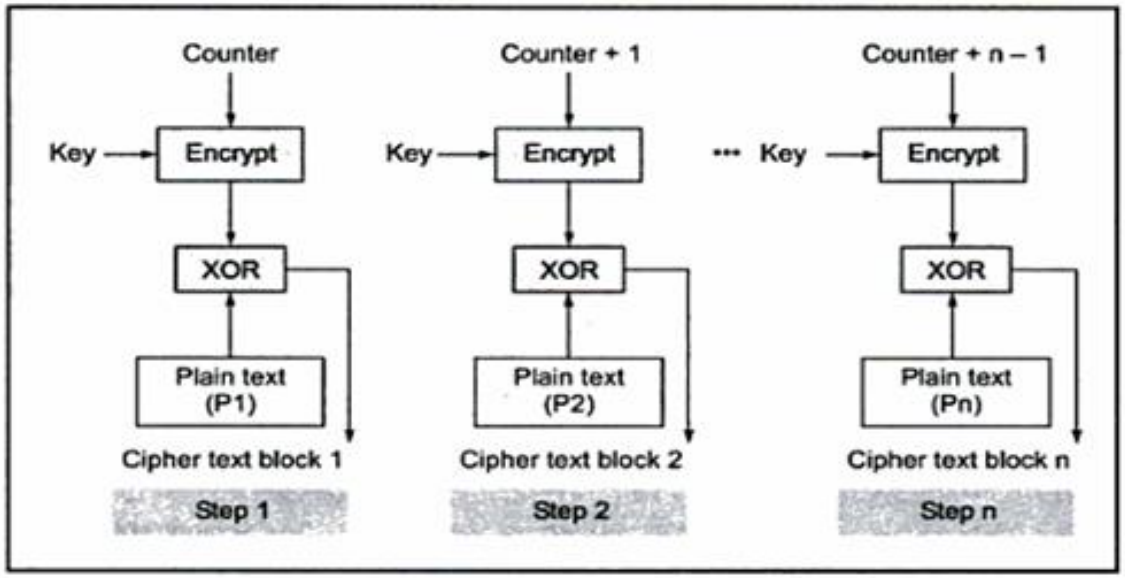
CFB – The overall encryption process

Output Feedback(OFB) Mode

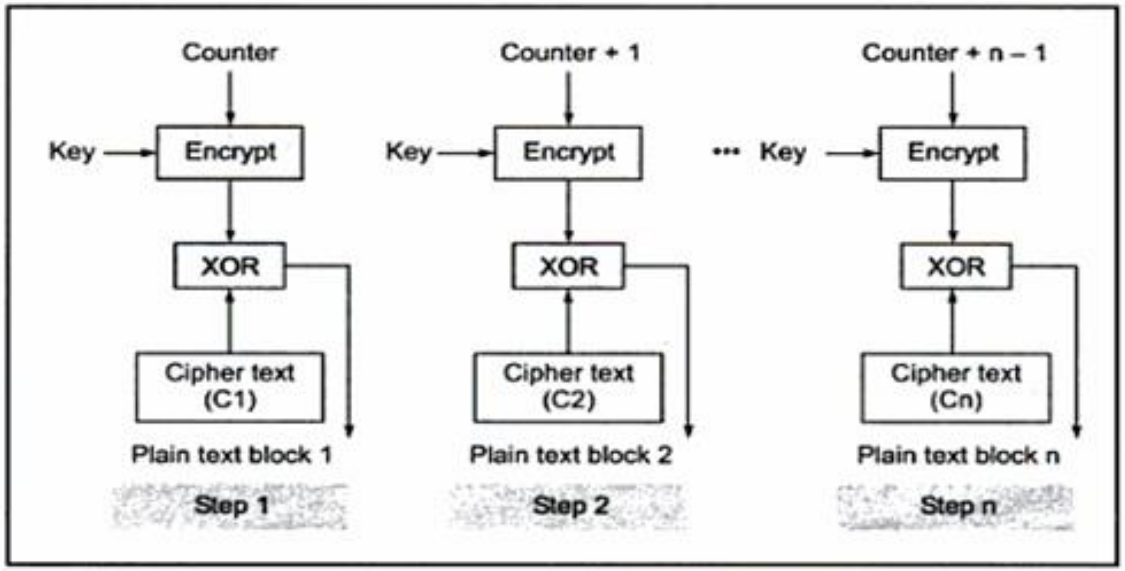


OFB – The overall encryption process

Counter(CTR) Mode



Counter (CTR) mode: The encryption process



Counter (CTR) mode: The decryption process

Details and usage

Electronic Code Book (ECB)	The same key independently encrypts blocks of text, 64 bits at a time.	Transmitting a single value in a secure fashion (e.g. password or key used for encryption).
Cipher Block Chaining (CBC)	64 bits of cipher text from the previous step and 64 bits of plain text of the next step are XORed together.	Encrypting blocks of text Authentication.
Cipher Feedback (CFB)	*K* bits of randomized cipher text from the previous step and *K* bits of plain text of the next step are XORed together.	Transmitting encrypted stream of data Authentication.
Output Feedback (OFB)	Similar to CFB, except that the input to the encryption step is the preceding DES output.	Transmitting encrypted stream of data.
Counter (CTR)	A counter and plain-text block are encrypted together, after which the counter is incremented.	Block-oriented transmissions Applications needing high speed.

Advantages and Disadvantages

Feature	ECB	CBC	CFB	OFB/Counter
Security Related Problems	Plain text patterns are not hidden. Input to the block cipher is the same as the plain text, and is not randomized. Plain text is easy to manipulate, blocks of text can be removed, repeated or exchanged.	Plain text blocks can be removed from the beginning and end of the message, and the bits of the first block can be altered.	Plain text blocks can be removed from the beginning and end of the message, and the bits of the first block can be altered.	Plain text is easy to manipulate. Altering cipher text alters plain text directly.
Security Related advantages	The same key can be used for encrypting multiple messages	XOR of plain text with previous cipher text block hides the plain text. The same key can be used for encrypting multiple messages.	Plain text patterns are hidden. The same key can be used for encrypting multiple messages, by using a different IV. Input to the block cipher is randomized.	Plain text patterns are hidden. The same key can be used for encrypting multiple messages, by using a different IV. Input to the block cipher is randomized.
Problem related to effectiveness	Size of cipher text is more than the plain text size by one padding block. Pre-processing is not possible.	Size of cipher text is more than the plain text size by one padding block. Pre-processing is not possible. Parallelism cannot be introduced in encryption.	Size of cipher text is the same as that of the plain text size. Parallelism cannot be introduced in encryption.	Size of cipher text is the same as that of the plain text size. Parallelism cannot be introduced (OFB only).

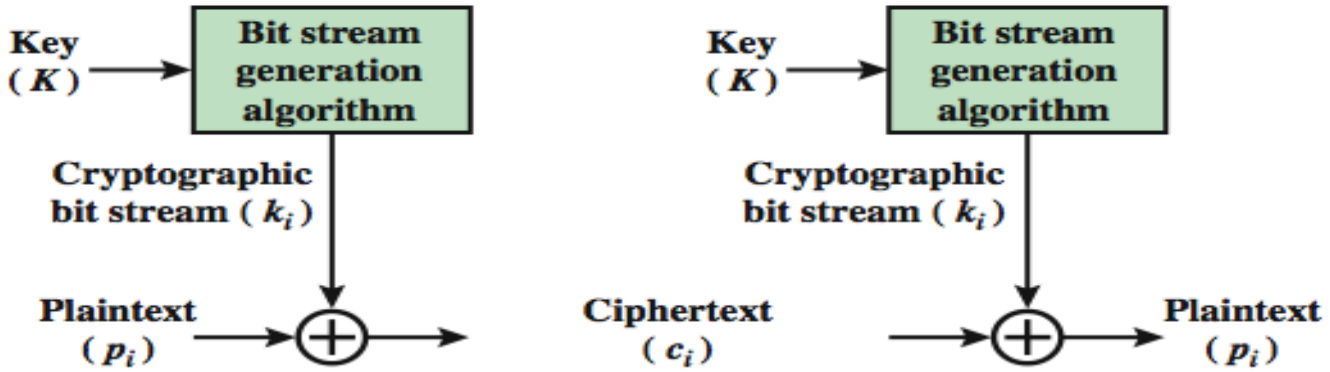
DATA ENCRYPTION STANDARD

Ref:Cryptography and Network Security-Atul Kahate

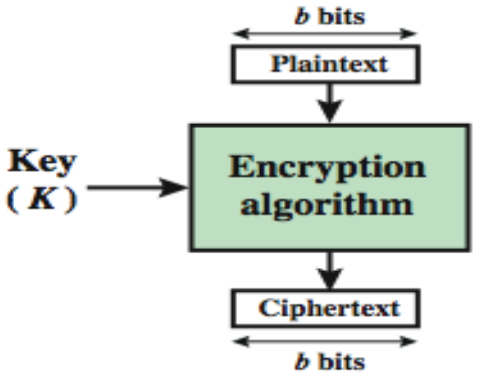
Block vs Stream Ciphers

- block ciphers process messages in blocks, each of which is then en/decrypted
- like a substitution on very big characters
  - 64-bits or more
- stream ciphers process messages a bit or byte at a time when en/decrypting
- many current ciphers are block ciphers
  - better analysed
  - broader range of applications

Block vs Stream Ciphers



(a) Stream Cipher Using Algorithmic Bit Stream Generator



(b) Block Cipher

Block Cipher Principles

- most symmetric block ciphers are based on a **Feistel Cipher Structure**
- needed since must be able to **decrypt** ciphertext to recover messages efficiently
- block ciphers look like an extremely large substitution
- would need table of 2^{64} entries for a 64-bit block
- instead create from smaller building blocks
- using idea of a product cipher

Claude Shannon and Substitution-Permutation Ciphers

- Claude Shannon introduced idea of substitution-permutation (S-P) networks in 1949 paper
- form basis of modern block ciphers
- S-P nets are based on the two primitive cryptographic operations seen before:
  - *substitution* (S-box)
  - *permutation* (P-box)
- provide *confusion* & *diffusion* of message & key

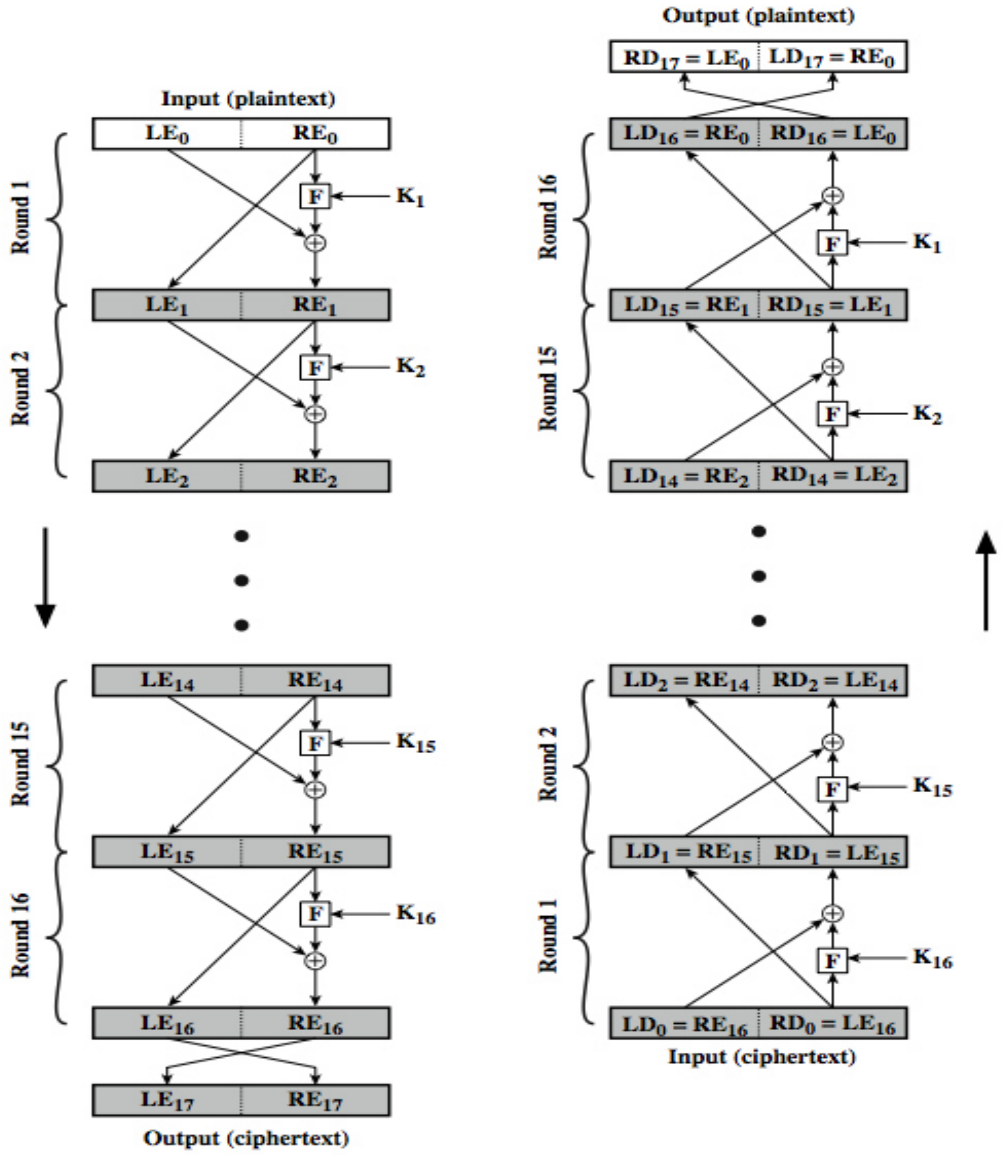
Confusion and Diffusion

- cipher needs to completely obscure statistical properties of original message
- a one-time pad does this
- more practically Shannon suggested combining S & P elements to obtain:
- **diffusion** – Increases the redundancy of the plain text by spreading it across rows and columns.
- **confusion** – makes relationship between ciphertext and key as complex as possible

Feistel Cipher Structure

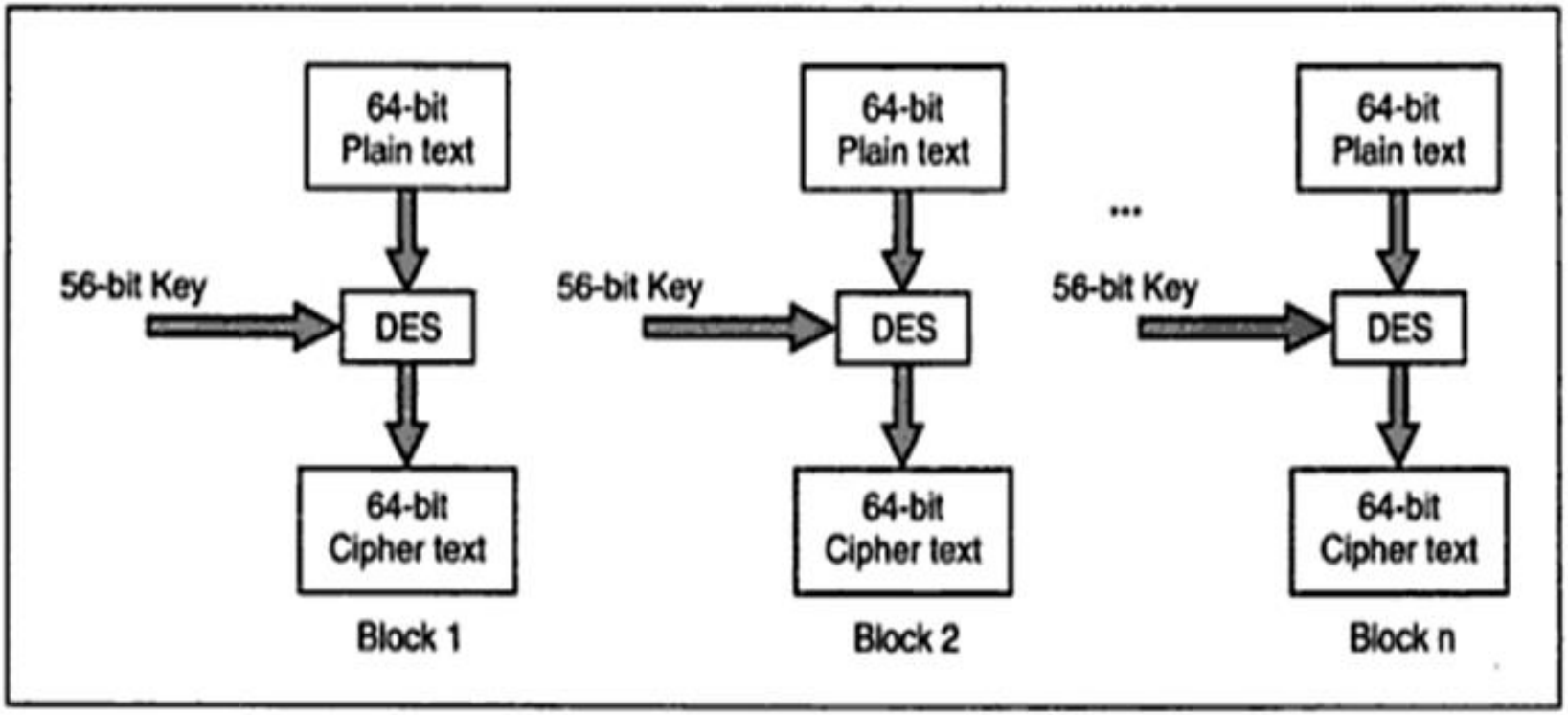
- Horst Feistel devised the **feistel cipher**
  - based on concept of invertible product cipher
- partitions input block into two halves
  - process through multiple rounds which
  - perform a substitution on left data half
  - based on round function of right half & subkey
  - then have permutation swapping halves
- implements Shannon's S-P net concept

Feistel Cipher Structure



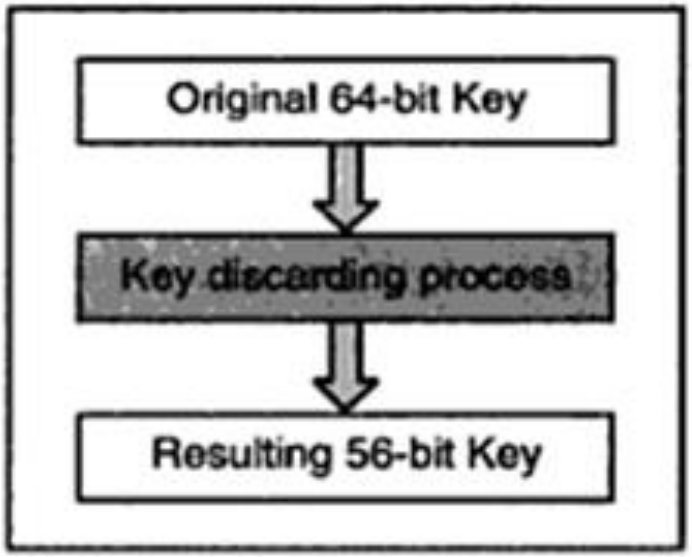
DES

1.Basic working principle



Discarding 8th bit of original Key

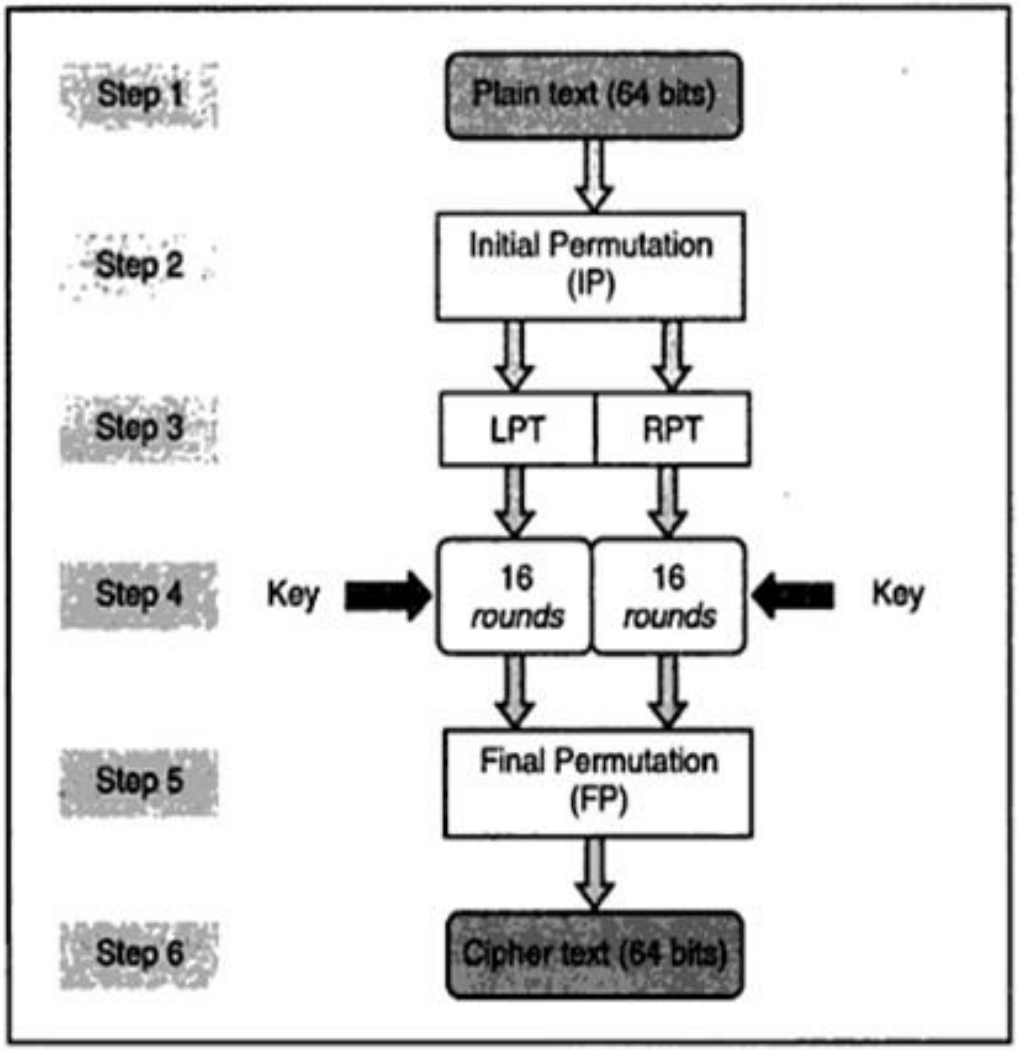
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64



Steps in DES

- In the first step , 64-bit plain text block is handed over to an initial permutation IP function.
- The initial permutation is performed on plain text.
- Initial permutation produces two halves of the permuted block; left plain text (LPT) and right plain text (RPT).
- Each LPT AND RPT goes through 16rounds of encryption process, each with its own key.
- At the end LPT and RPT are rejoined and a final permutation (FP) is performed on the combined block.
- The result of this process is 64-bit cipher text.

Broad Level steps in DES



2.Initial permutation

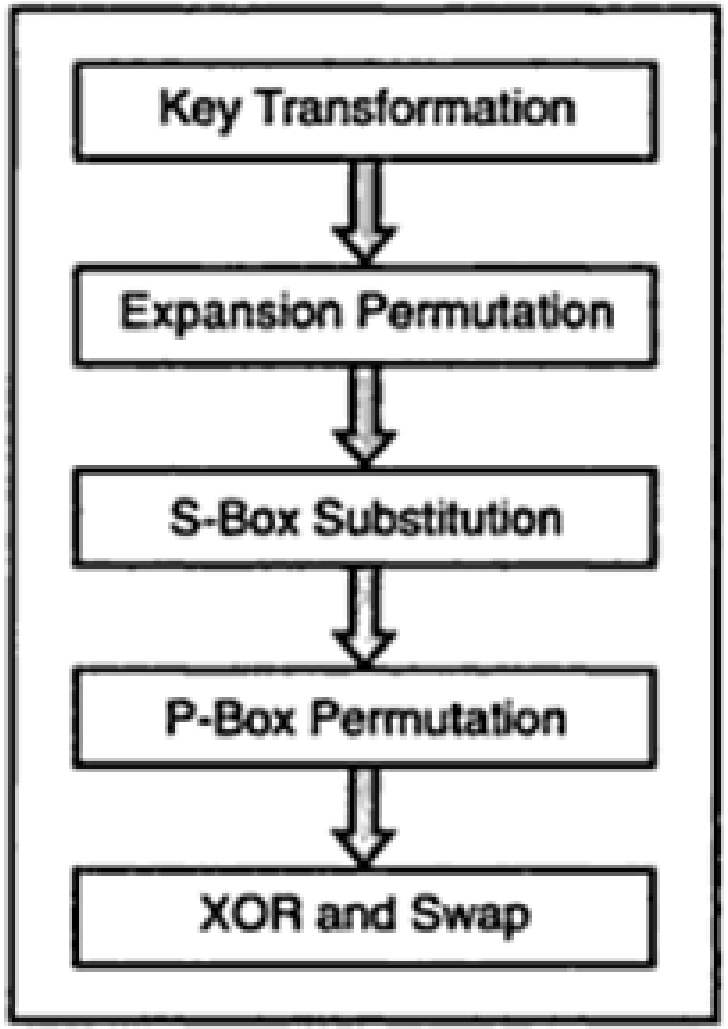
Table 3.1 *Idea of IP*

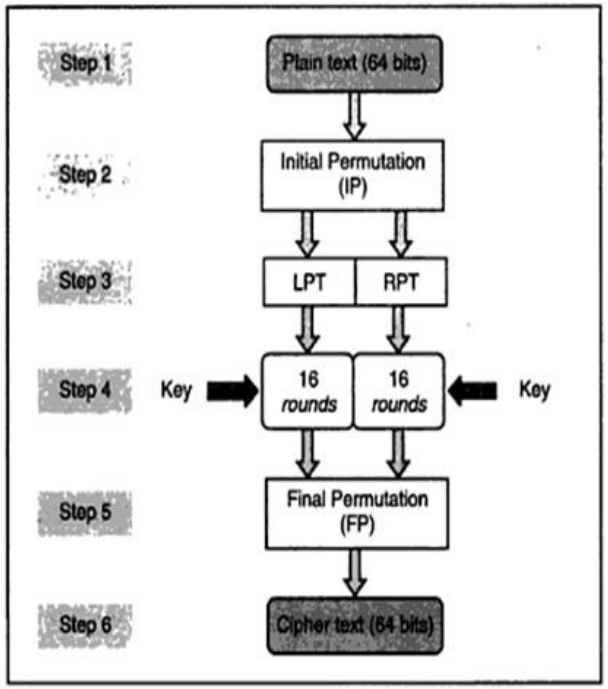
Bit position in the plain text block	*To be overwritten with the contents of this bit position*
1	58
2	50
3	42
..	..
64	7

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

Fig. 3.20 *Initial Permutation (IP) table*

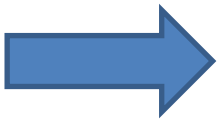
3.Details of one Round in DES





Step 1: Key Transformation

Left shift



Round	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Number of key bits shifted	1	1	2	2	2	2	2	2	1	2	2	2	2	2	2	1

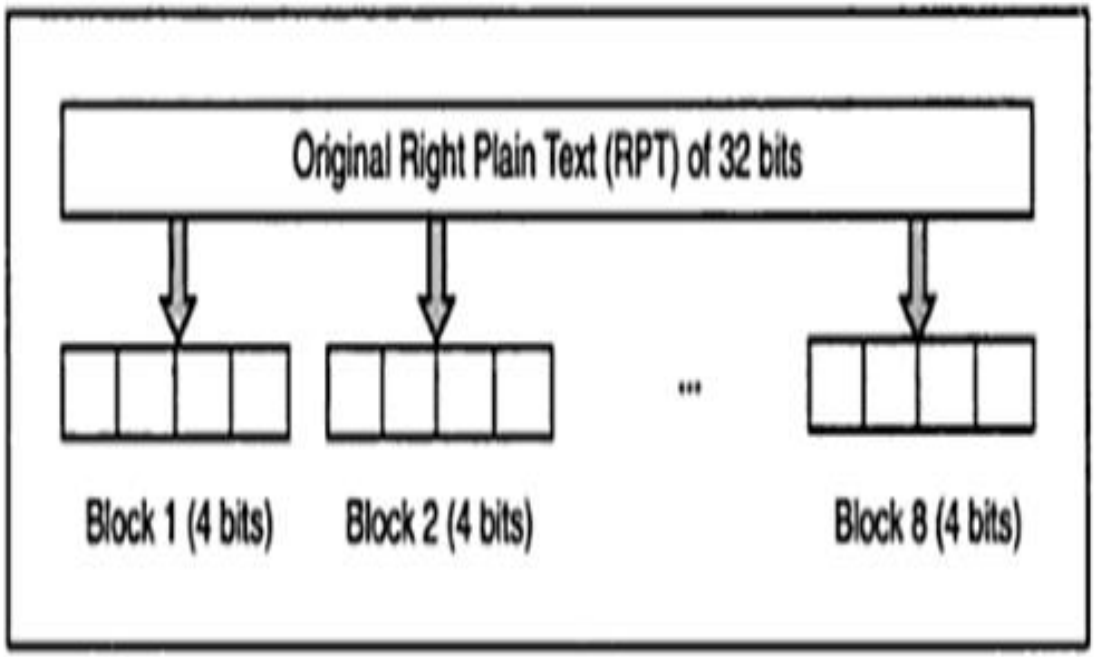
Compression Permutation

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

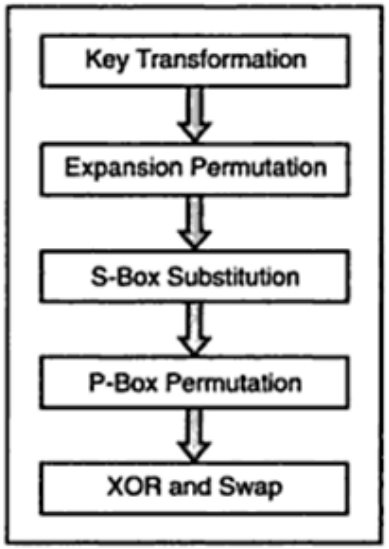
$C_0 = 1111000011001100101010101111$

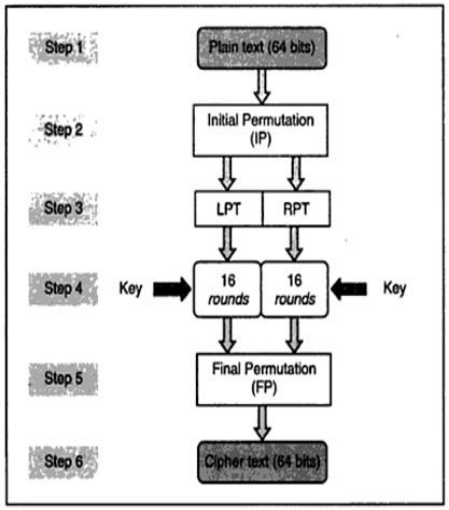
$C_1 = 1110000110011001010101011111$

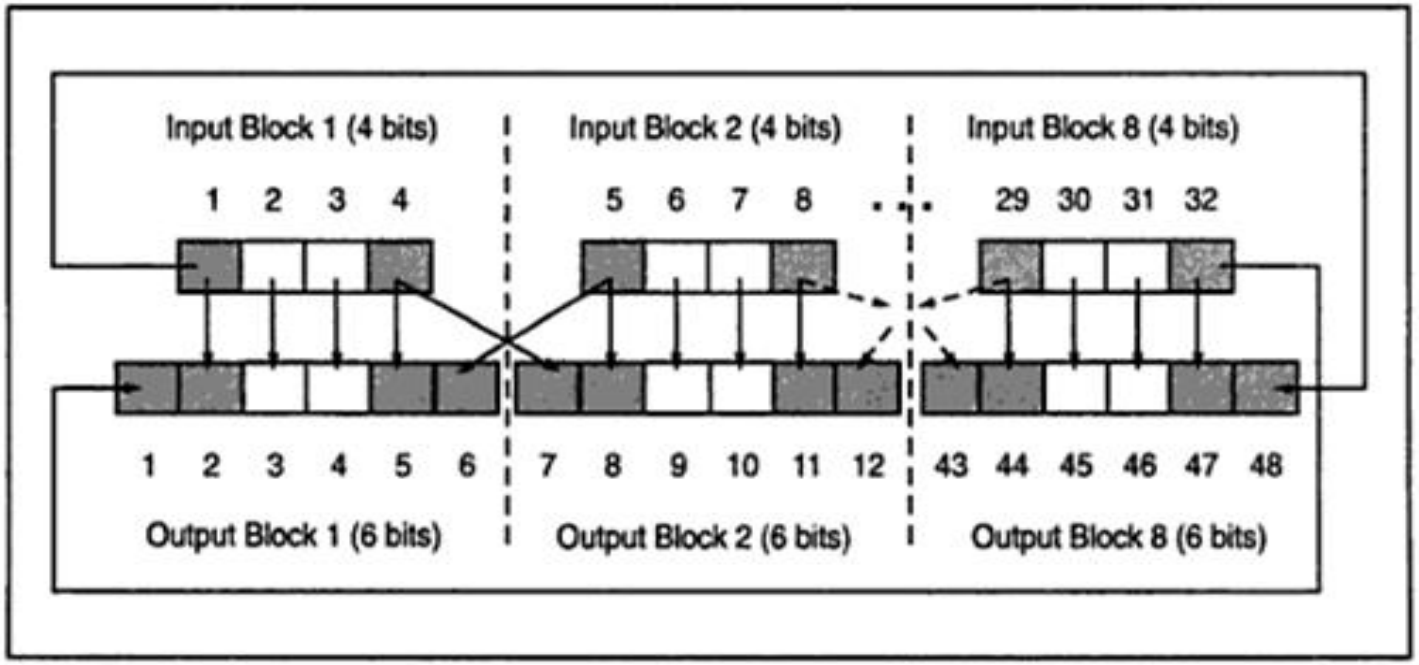
Step 2 Expansion Permutation



Division of 32-bit RPT into eight 4-bit blocks





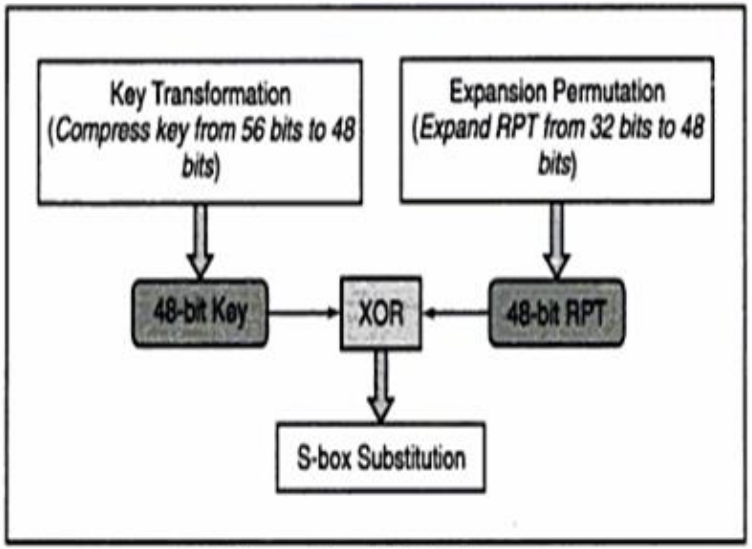


RPT expansion permutation process

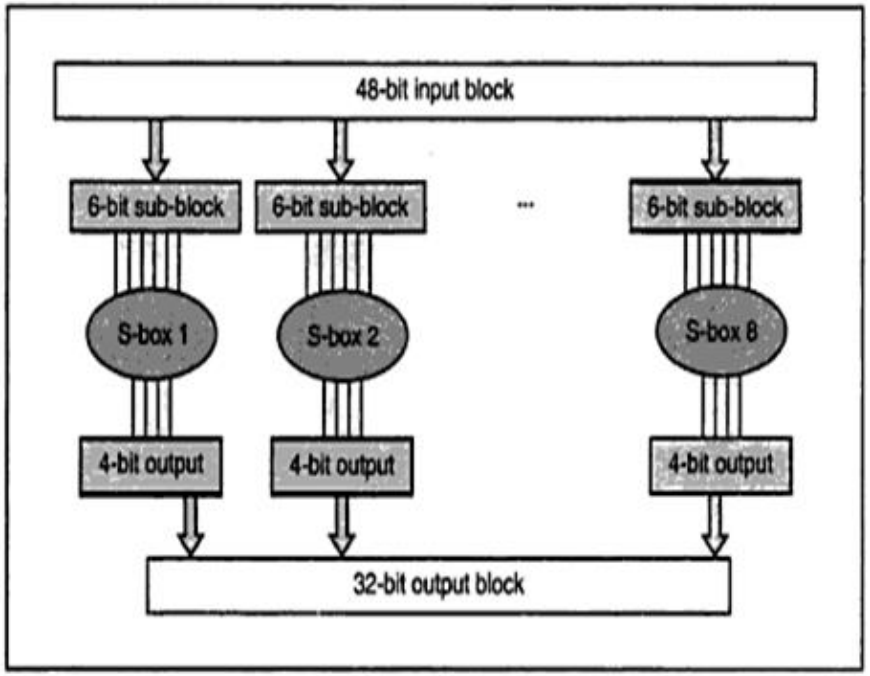
32	1	2	3	4	5	4	5	6	7	8	9
8	9	10	11	12	13	12	13	14	15	16	17
16	17	18	19	20	21	20	21	22	23	24	25
24	25	26	27	28	29	28	29	30	31	32	1

RPT expansion permutation table

Step 3:S Box substitution



Way to S-box Substitution



S-box substitution

14	4	13	1	2	15	11	8	3	10	6	12	5	9	0	7
0	15	7	4	14	2	13	1	10	6	12	11	9	5	3	8
4	1	14	8	13	6	2	11	15	12	9	7	3	10	5	0
15	12	8	2	4	9	1	7	5	11	3	14	10	0	6	13

S-box 1

15	1	8	14	6	11	3	4	9	7	2	13	12	0	5	10
3	13	4	7	15	2	8	14	12	0	1	10	6	9	11	5
0	14	7	11	10	4	13	1	5	8	12	6	9	3	2	15
13	8	10	1	3	15	4	2	11	6	7	12	0	5	14	9

S-box 2

10	0	9	14	6	3	15	5	1	13	12	7	11	4	2	8
13	7	0	9	3	4	6	10	2	8	5	14	12	11	15	1
13	6	4	9	8	15	3	0	11	1	2	12	5	10	14	7
1	10	13	0	6	9	8	7	4	15	14	3	11	5	2	12

S-box 3

7	13	14	3	0	6	9	10	1	2	8	5	11	12	4	15
13	8	11	5	6	15	0	3	4	7	2	12	1	10	14	9
10	6	9	0	12	11	7	13	15	1	3	14	5	2	8	4
3	15	0	6	10	1	13	8	9	4	5	11	12	7	2	14

S-box 4

2	12	4	1	7	10	11	6	8	5	3	15	13	0	14	9
14	11	2	12	4	7	13	1	5	0	15	10	3	9	8	6
4	2	1	11	10	13	7	8	15	9	12	5	6	3	0	14
11	8	12	7	1	14	2	13	6	15	0	9	10	4	5	3

S-box 5

12	1	10	15	9	2	6	8	0	13	3	4	14	7	5	11
10	15	4	2	7	12	9	5	6	1	13	14	0	11	3	8
9	14	15	5	2	8	12	3	7	0	4	10	1	13	11	6
4	3	2	12	9	5	15	10	11	14	1	7	6	0	8	13

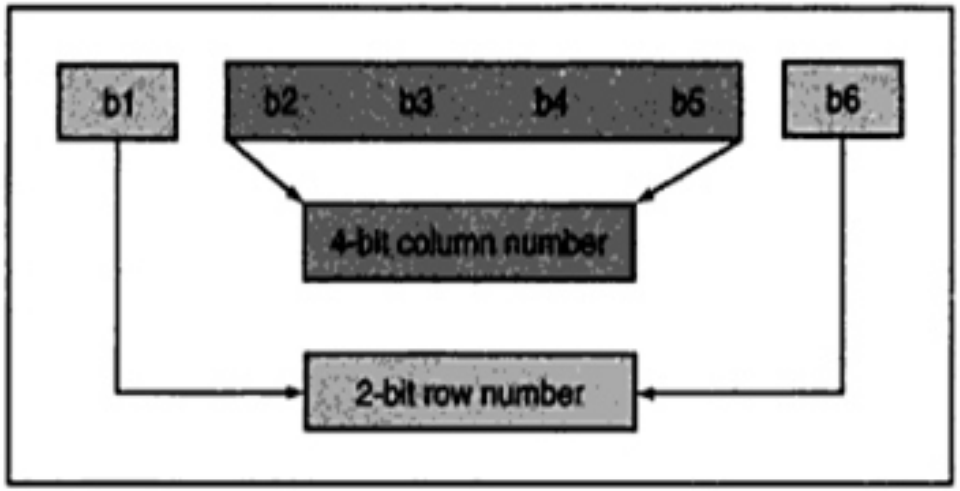
S-box 6

4	11	2	14	15	0	8	13	3	12	9	7	5	10	6	1
13	0	11	7	4	9	1	10	14	3	5	12	2	15	8	6
1	4	11	13	12	3	7	14	10	15	6	8	0	5	9	2
6	11	13	8	1	4	10	7	9	5	0	15	14	2	3	12

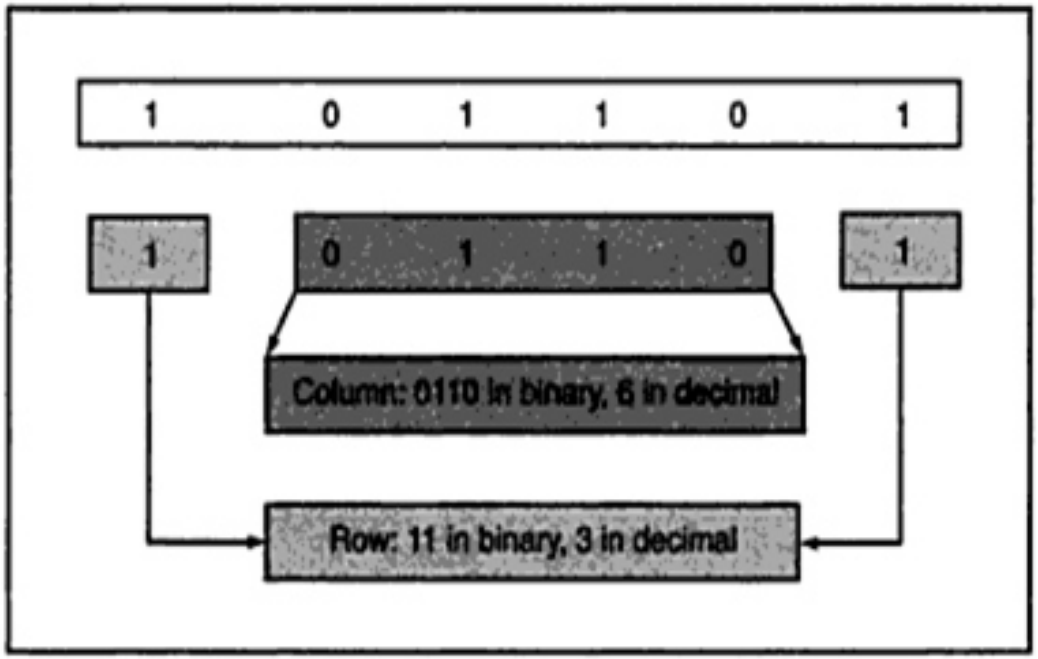
S-box 7

13	2	8	4	6	15	11	1	10	9	3	14	5	0	12	7
1	15	13	8	10	3	7	4	12	5	6	11	0	14	9	2
7	11	4	1	9	12	14	2	0	6	10	13	15	3	5	8
2	1	14	7	4	10	8	13	15	12	9	0	3	5	6	11

S-box 8



Selecting an entry in a S-box based on the 6-bit input

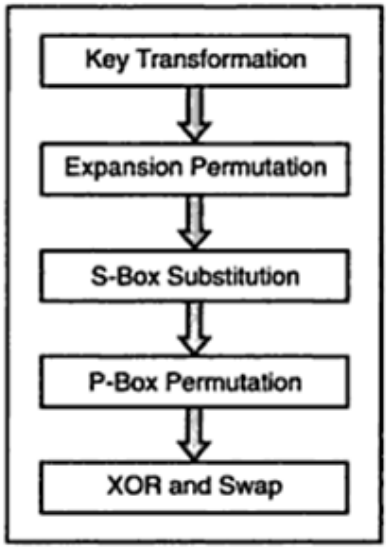


Example of selection of S-box output based on the input

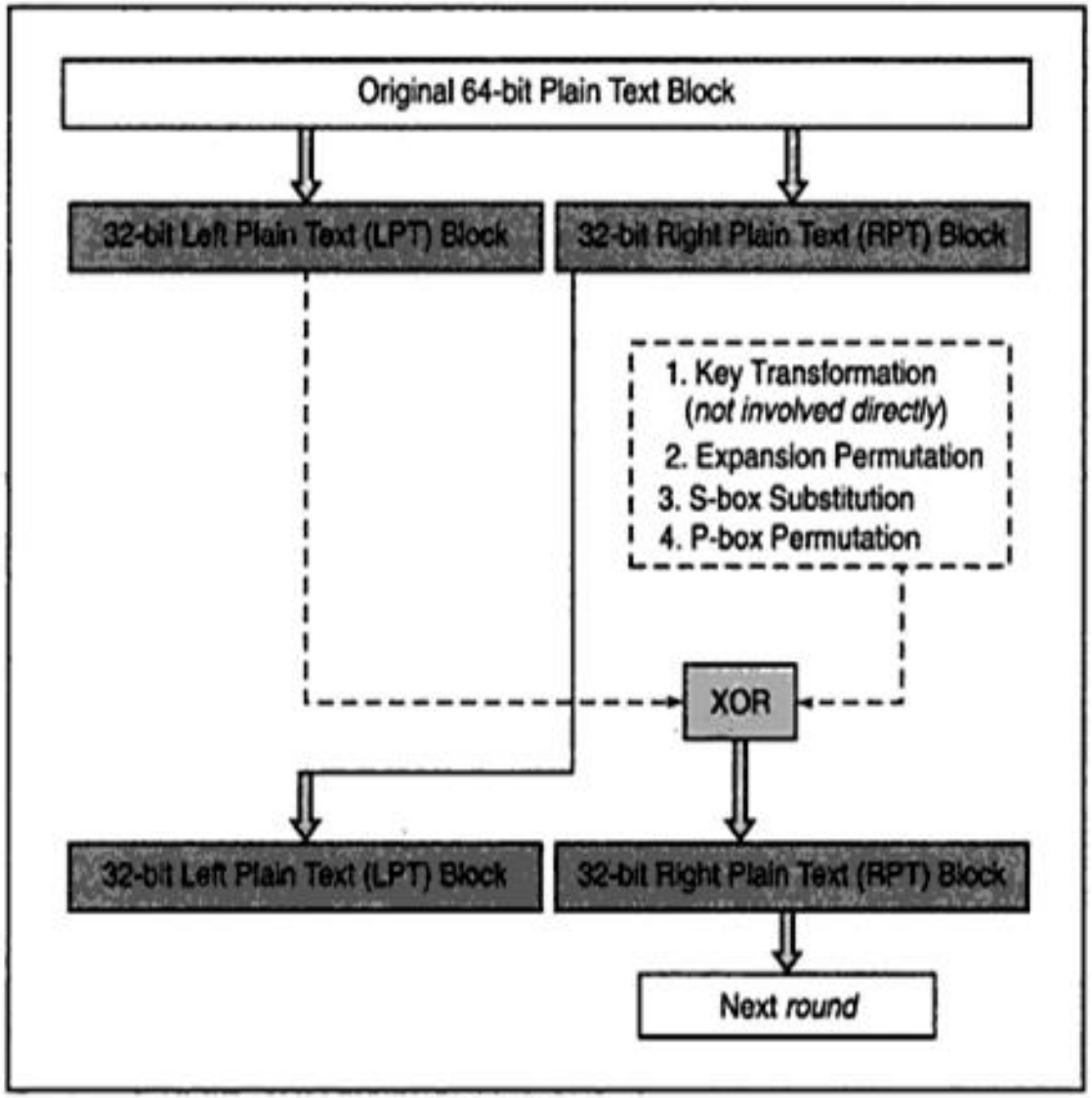
Step 4:P Box Permutation

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

P-box permutation



Step 5:XOR and Swap

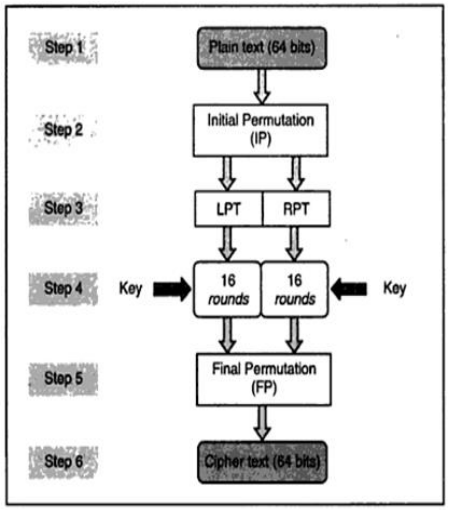


XOR and Swap

4.Final Permutation

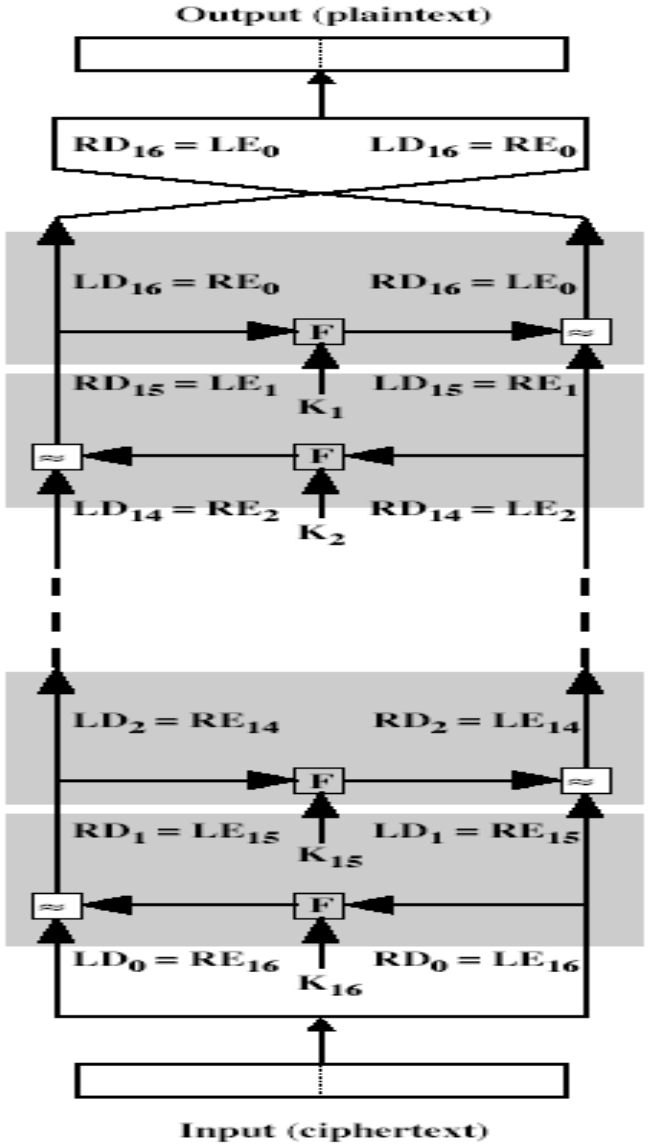
40	8	48	16	56	24	64	32	39	7	47	15	55	23	63	31
38	6	46	14	54	22	62	30	37	5	45	13	53	21	61	29
36	4	44	12	52	20	60	28	35	3	43	11	51	19	59	27
34	2	42	10	50	18	58	26	33	1	41	9	49	17	57	25

Fig. 3.34 *Final Permutation*



DES Decryption

- The same algorithm as encryption.
- Reversed the order of key (Key_{16}, Key_{15}, … Key_1).
- For example:
  - IP undoes IP^{-1} step of encryption.
  - 1st round with SK16 undoes 16th encrypt round.



Strength of DES

- 56-bit keys have $2^{56} = 7.2 \times 10^{16}$ values
  - Brute force search looks hard.
  - A machine performing one DES encryption per microsecond would take more than a thousand year to break the cipher.
- The Nature of the DES algorithm

- Avalanche effect in DES
  - If a small change in either the plaintext or the key, the ciphertext should change markedly.
- DES exhibits a strong avalanche effect.

ULTIMATE

DES was proved insecure

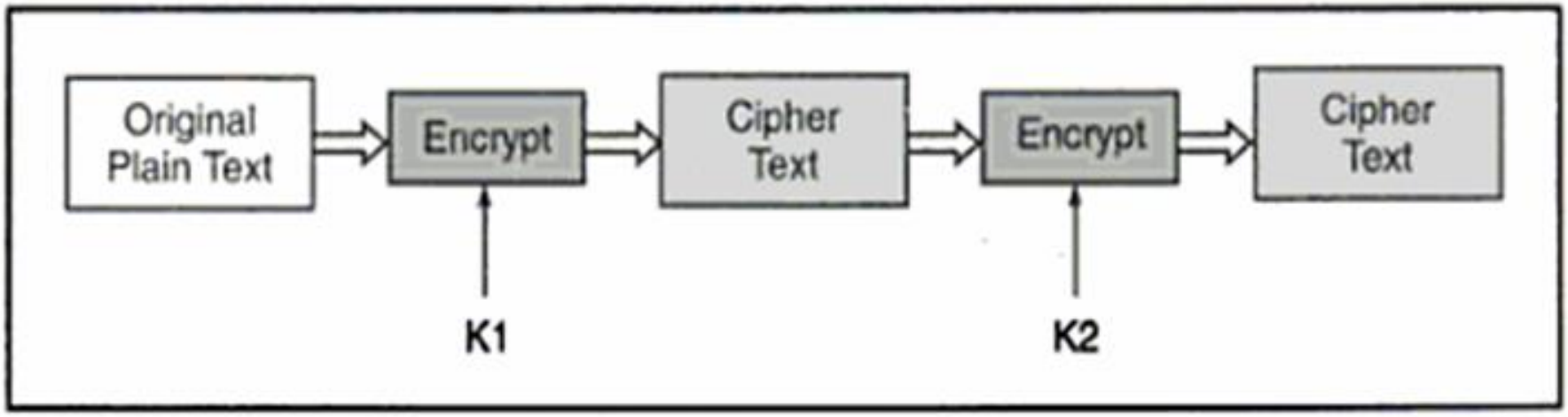
- In 1997 on Internet in a few months
- in 1998 on dedicated h/w (EFF) in a few days
- In 1999 above combined in 22hrs!

THANK YOU

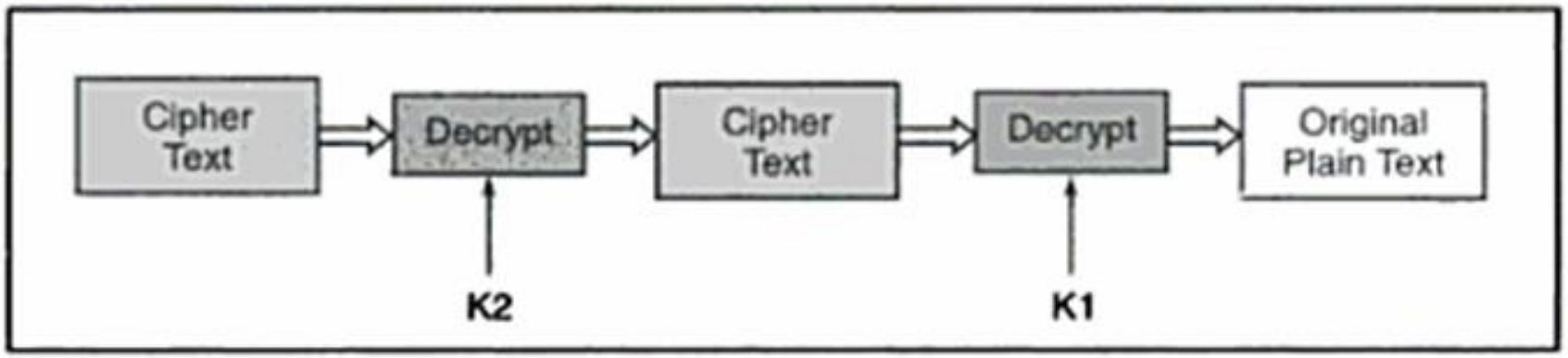
TRIPLE DES

Ref:Cryptography and Network Security-Atul Kahate

Double DES

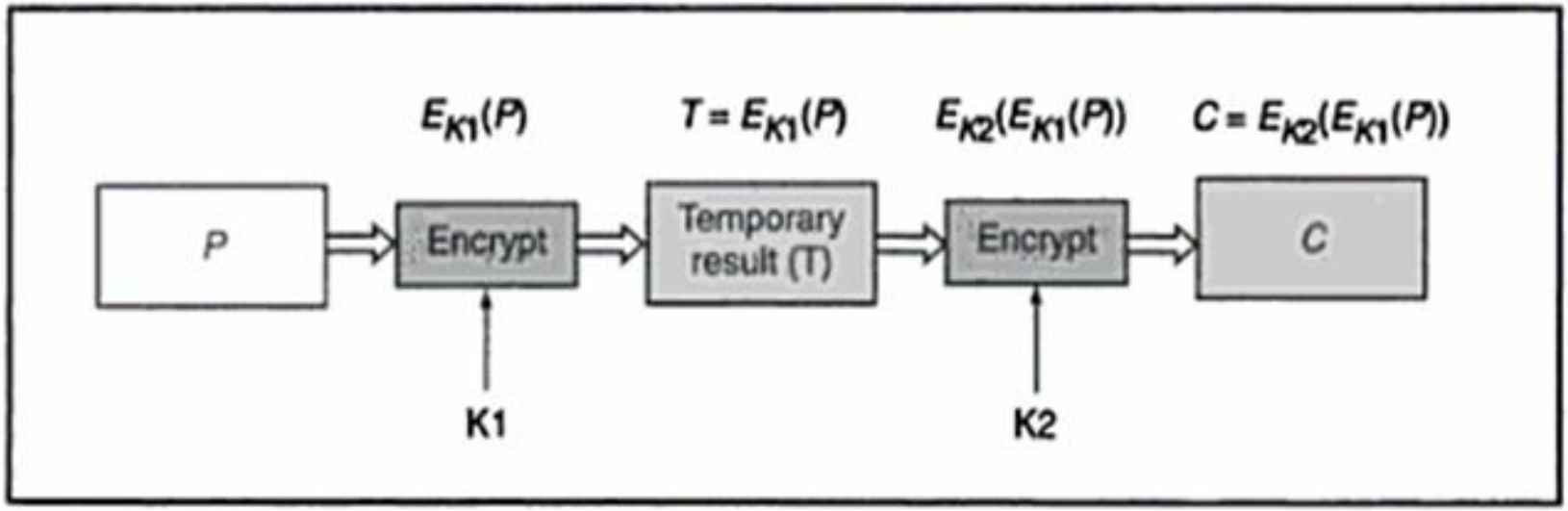


Double DES encryption

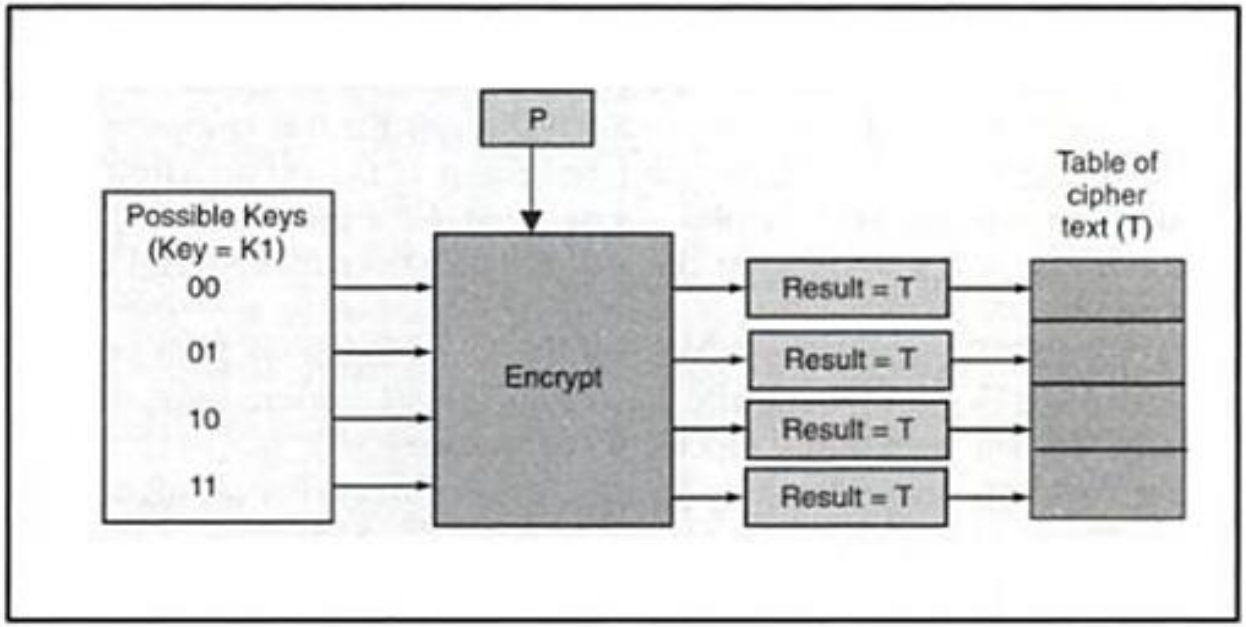


Double DES decryption

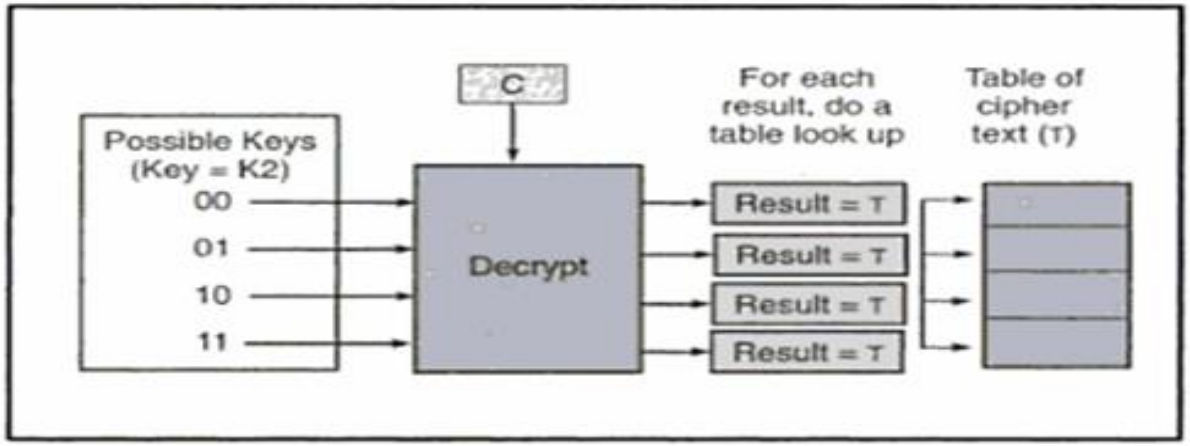
Mathematical expression of double DES



- Merkle and Millman introduced the concept- Meet in the middle attack



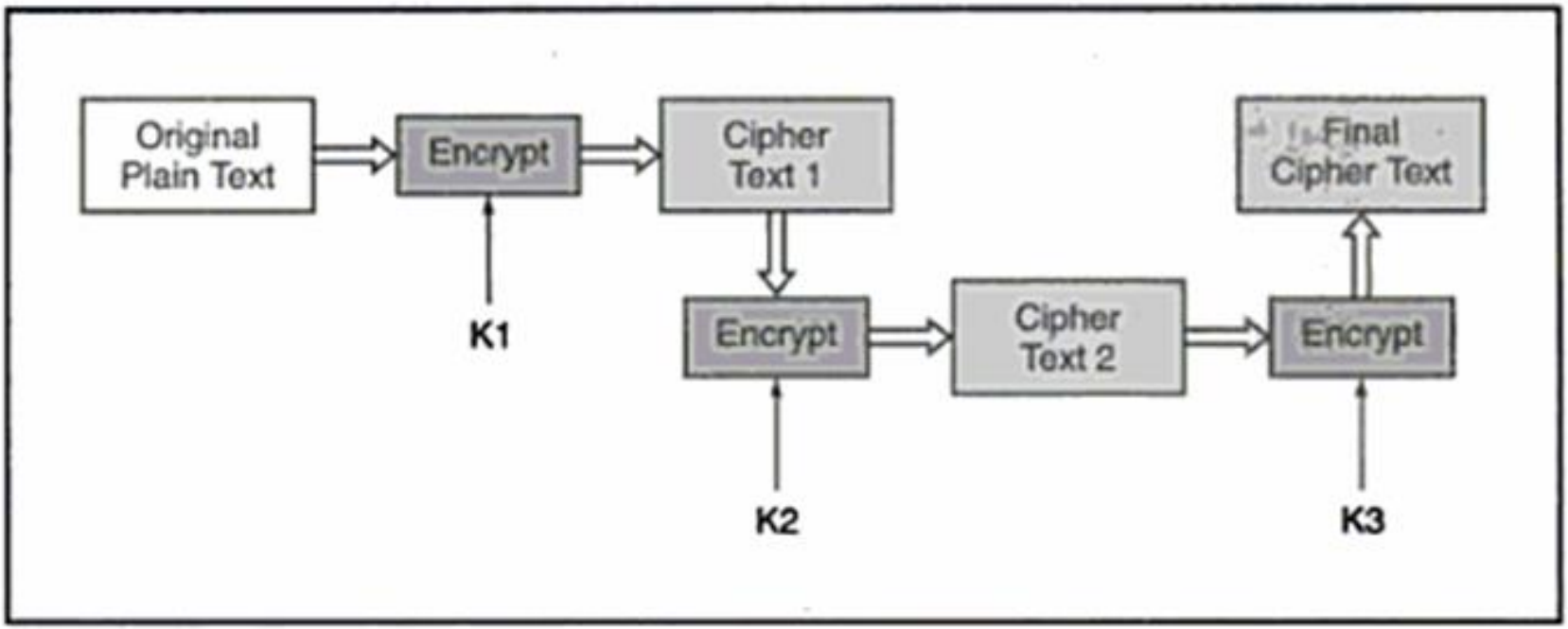
Conceptual view of the cryptanalyst's encrypt operation



Conceptual view of the cryptanalyst's decrypt operation

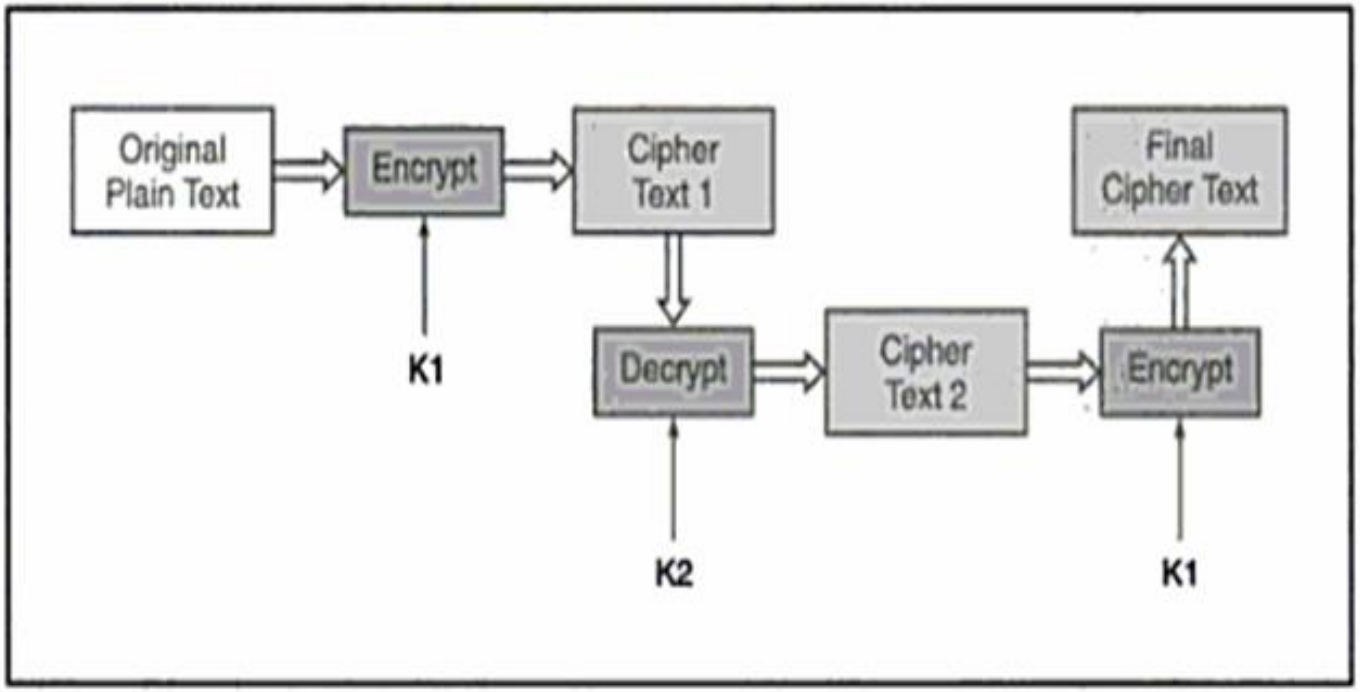
$$T = E_{K1}(P) = D_{K2}(C)$$

Triple DES with three keys



- Having three different keys is difficult in practical situation

Encrypt-Decrypt-Encrypt Mode Triple DES with two keys



THANK YOU

Block Cipher Design Principles

Ref:Information Security: Principles and Practices, 2nd Edition

Design Criteria for DES S-boxes

1. No output bit of any S-box should be too close to a linear function of the input bits
2. Each row of an S-box should include all 16 possible output bit combinations
3. If two inputs to an S-box differ in exactly one bit, the outputs must differ in at least two bits
4. If two inputs to an S-box differ in the two middle bits, the outputs must differ in >= 2 bits
5. If two inputs differ in their first two bits and are identical in last two bits, the two outputs must not be the same
6. For any nonzero 6-bit difference in inputs, no more than 8 of the 32 pairs with that difference may result in the same output difference

Criteria for DES P-box

1. The four output bits from each S-box are distributed so that two are "middle" bits and two are "outer" bits in their nibbles
2. The four output bits from each S-box affect six different S-boxes in the next round, and no two affect the same S-box
3. For two S-boxes, j and k, if an output bit from Sj affects a middle bit of Sk in the next round, then an output bit from Sk cannot affect a middle bit of Sj (so Sj output can't be a middle bit of Sj in next round)

DES Design Criteria

- Reported by Coppersmith
- 7 criteria for S-boxes provide for
  - non-linearity
  - resistance to differential cryptanalysis
  - good confusion
- 3 criteria for permutation P provide for
  - increased diffusion

Design criteria for F

- Non linearity-the more difficult it is to approximate F by a set of linear equations, the more non linear F is.
- The algorithm should have good avalanche properties.
- Stringent version is called strict Avalanche Criterion(SAC)
- Bit independence criterion(BIC)

Advanced Encryption Standard

Ref:Cryptography and Network Security Principles and Practice, 5th Edition by William Stallings

NIST Criteria to Evaluate Potential Candidates

- Security: The effort to crypt analyze an algorithm.
- Cost: The algorithm should be practical in a wide range of applications.
- Algorithm and Implementation Characteristics : Flexibility, simplicity etc.

5 final candidates have been chosen out of 15

NIST Criteria

- General Security
- Software Implementations
- Hardware Implementations
- Restricted-Space Environments
- Attacks on Implementations
- Encryption vs. Decryption
- Key Agility
- Potential for Instruction-Level Parallelism
- Other versatility and Flexibility

NIST selected Rijndael as the proposed AES algorithm

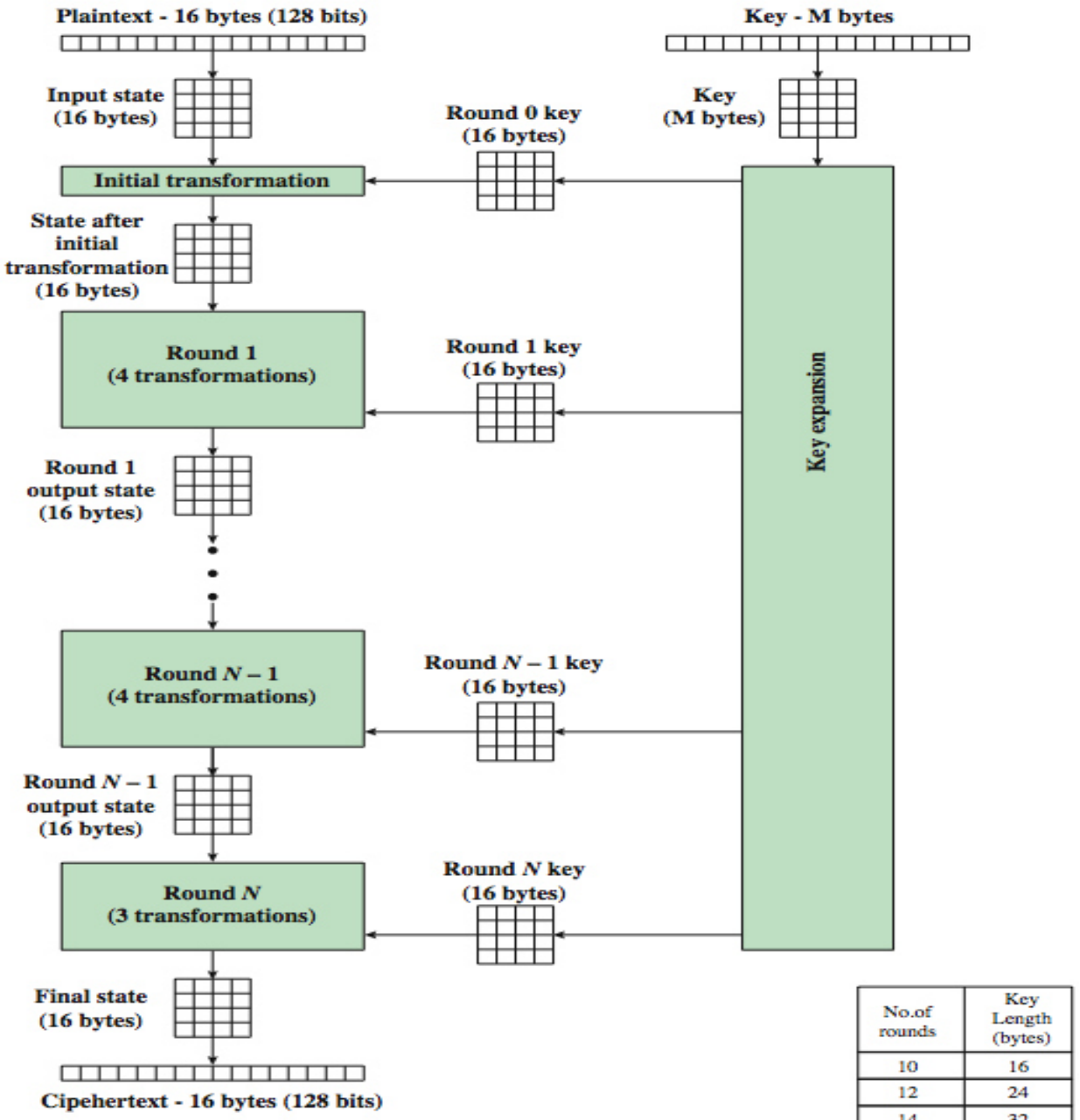
AES Origin

- clear a replacement for DES was needed
  - have theoretical attacks that can break it
  - have demonstrated exhaustive key search attacks
- can use Triple-DES – but slow, has small blocks
- US NIST(National institute of standards and technology) issued call for ciphers in 1997
- 15 candidates accepted in Jun 98
- 5 were shortlisted in Aug-99
- Rijndael was selected as the AES in Oct-2000
- issued as FIPS PUB 197 standard in Nov-2001

The AES Cipher - Rijndael

- Designed by Rijmen-Daemen in Belgium
- has 128/192/256 bit keys, 128 bit block size (data)
- an **iterative** rather than **Feistel** cipher
  - processes data as block of 4 columns of 4 bytes
  - operates on entire data block in every round
- Designed to have:
  - resistance against known attacks
  - speed and code compactness on many CPUs
  - design simplicity

AES Encryption Process

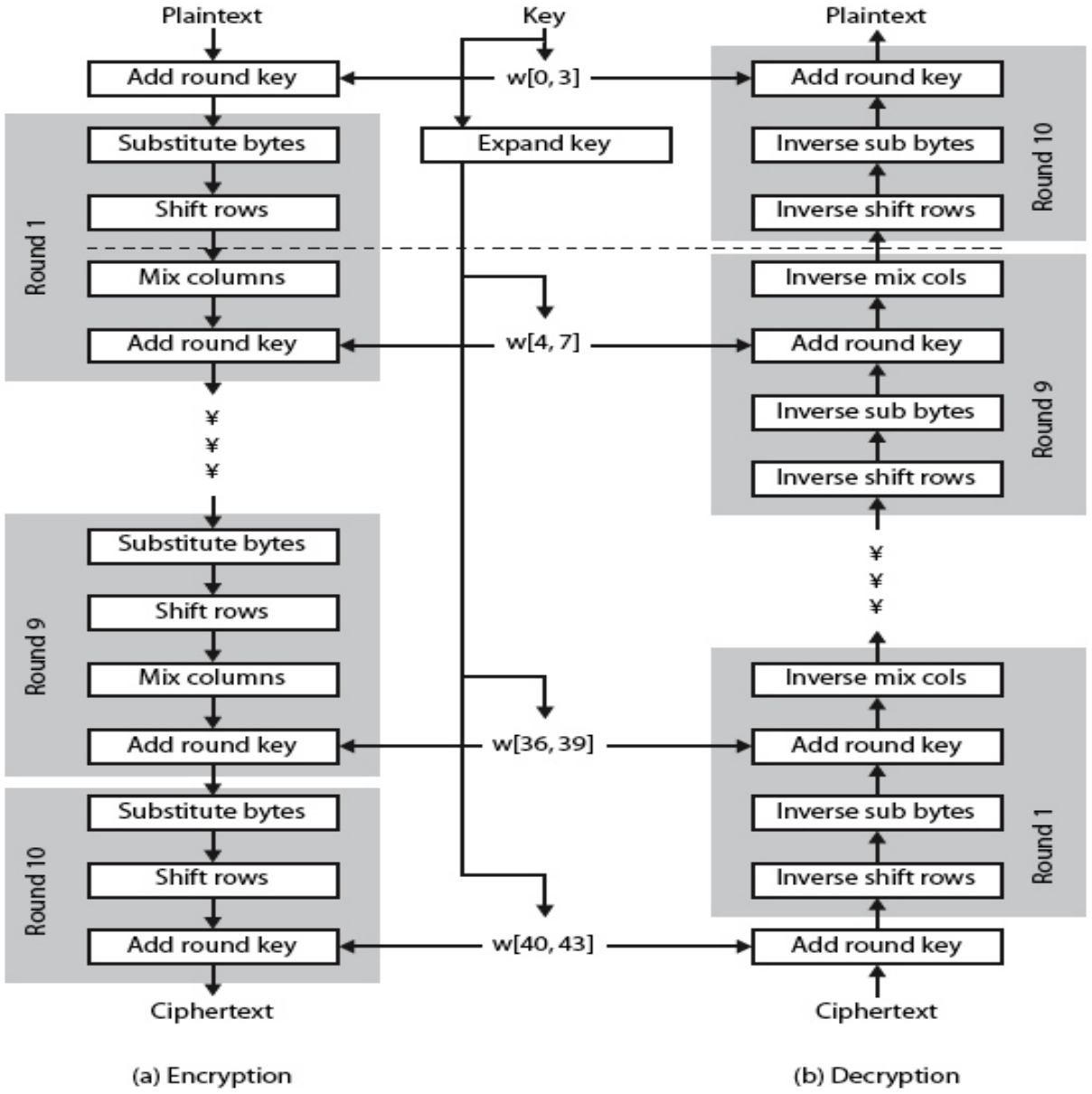


No.of rounds	Key Length (bytes)
10	16
12	24
14	32

AES Structure

- data block of 4 columns of 4 bytes is state
- key is expanded to array of words
- has 10/12/14 rounds in which state undergoes:
  - byte substitution (1 S-box used on every byte)
  - shift rows (permute bytes between groups/columns)
  - mix columns (subs using matrix multiply of groups)
  - add round key (XOR state with key material)
  - view as alternating XOR key & scramble data bytes
- initial XOR key material & incomplete last round
- with fast XOR & table lookup implementation

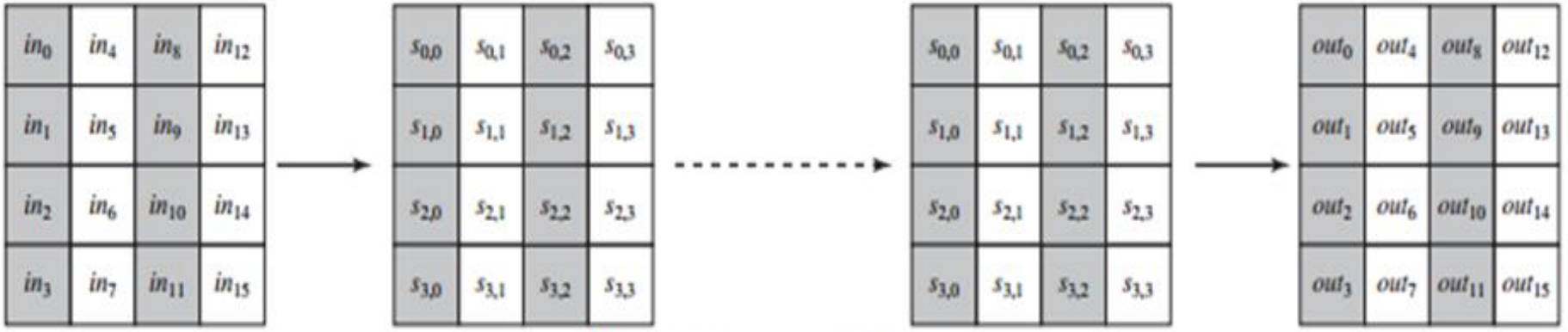
AES Structure



Comments on Overall Structure of AES

- an iterative rather than Feistel cipher
- key expanded into array of 32-bit words
  - four words form round key in each round
- 4 different stages are used as shown
- Has a simple structure
- only AddRoundKey uses key
- Add RoundKey a form of Vernam cipher
- Each stage is easily reversible
- Decryption uses keys in reverse order
- Decryption does recover plaintext
- Final round has only 3 stages

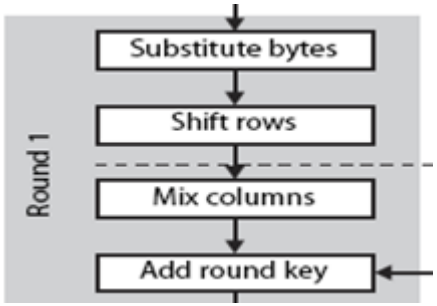
AES Data Structure



(a) Input, state array, and output

(b) Key and expanded key

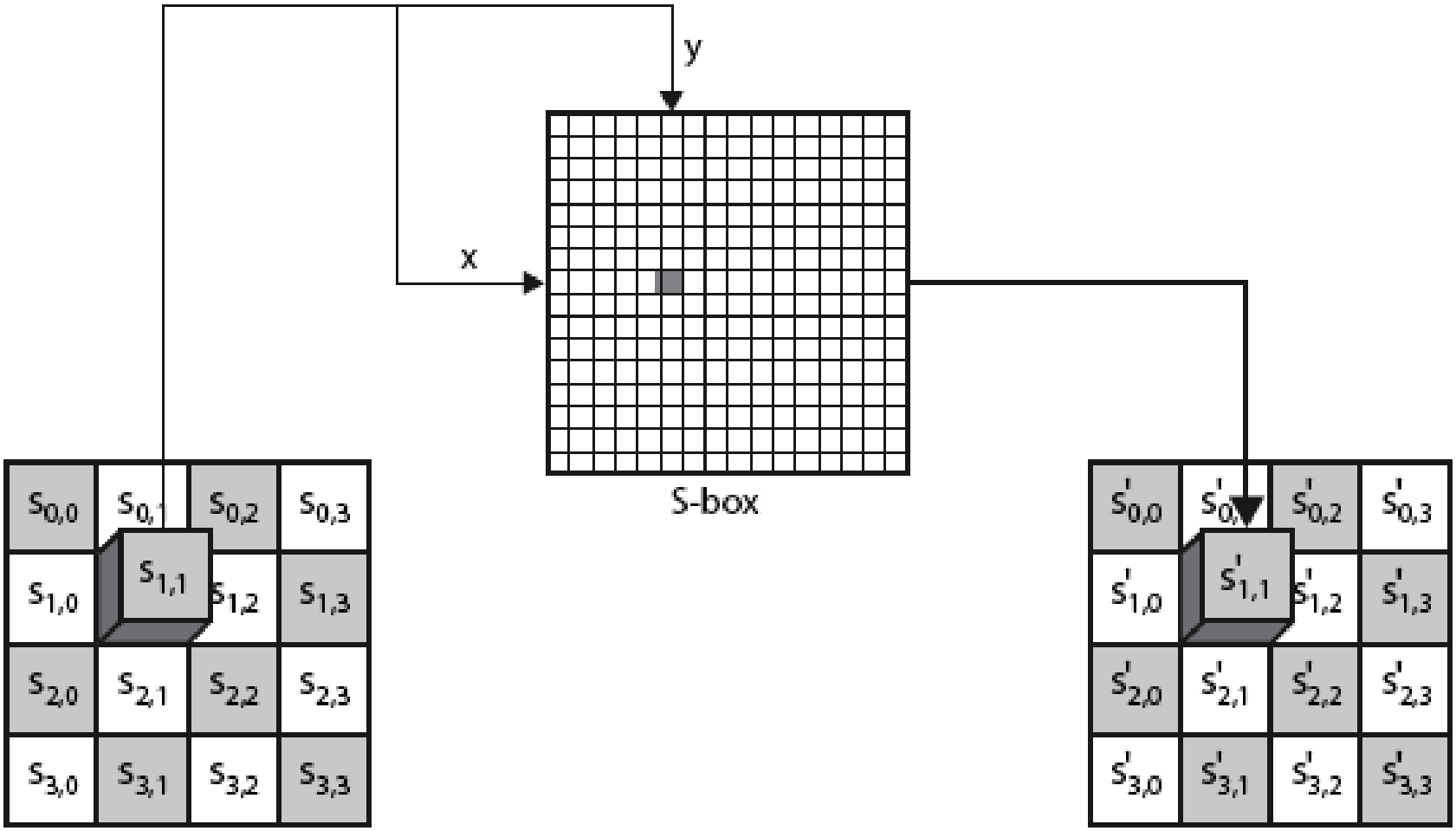
Substitute Bytes Transformation



- a simple substitution of each byte
- uses one table of 16x16 bytes containing a permutation of all 256 8-bit values
- each byte of state is replaced by byte indexed by row (left 4-bits) & column (right 4-bits)
  - eg. byte {95} is replaced by byte in row 9 column 5
  - which has value {2A}
- S-box constructed using defined transformation of values in GF(2^8)
- designed to be resistant to all known attacks

Substitute Bytes

https://www.quora.com/How-is-an-S-box-constructed-in-AES



S BOX

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

Inverse S Box

x \ y	0	1	2	3	4	5	6	7	8	9	a	b	c	d	e	f
0	52	09	6a	d5	30	36	a5	38	bf	40	a3	9e	81	f3	d7	fb
1	7c	e3	39	82	9b	2f	ff	87	34	8e	43	44	c4	de	e9	cb
2	54	7b	94	32	a6	c2	23	3d	ee	4c	95	0b	42	fa	c3	4e
3	08	2e	a1	66	28	d9	24	b2	76	5b	a2	49	6d	8b	d1	25
4	72	f8	f6	64	86	68	98	16	d4	a4	5c	cc	5d	65	b6	92
5	6c	70	48	50	fd	ed	b9	da	5e	15	46	57	a7	8d	9d	84
6	90	d8	ab	00	8c	bc	d3	0a	f7	e4	58	05	b8	b3	45	06
7	d0	2c	1e	8f	ca	3f	0f	02	c1	af	bd	03	01	13	8a	6b
8	3a	91	11	41	4f	67	dc	ea	97	f2	cf	ce	f0	b4	e6	73
9	96	ac	74	22	e7	ad	35	85	e2	f9	37	e8	1c	75	df	6e
a	47	f1	1a	71	1d	29	c5	89	6f	b7	62	0e	aa	18	be	1b
b	fc	56	3e	4b	c6	d2	79	20	9a	db	c0	fe	78	cd	5a	f4
c	1f	dd	a8	33	88	07	c7	31	b1	12	10	59	27	80	ec	5f
d	60	51	7f	a9	19	b5	4a	0d	2d	e5	7a	9f	93	c9	9c	ef
e	a0	e0	3b	4d	ae	2a	f5	b0	c8	eb	bb	3c	83	53	99	61
f	17	2b	04	7e	ba	77	d6	26	e1	69	14	63	55	21	0c	7d

Substitute Bytes Example

EA	04	65	85
83	45	5D	96
5C	33	98	B0
F0	2D	AD	C5

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

- The S-box is generated by determining the multiplicative inverse for a given number in Rijndael's Galois Field

  https://www.samiam.org/galois.html

- The multiplicative inverse is then transformed using the following affine transformation matrix:

```
1 1 0 0 0 1 1 1 1
2 1 1 0 0 0 1 1 1
3 1 1 1 0 0 0 1 1
4 1 1 1 1 0 0 0 1
5 1 1 1 1 1 0 0 0
6 0 1 1 1 1 1 0 0
7 0 0 1 1 1 1 1 0
8 0 0 0 1 1 1 1 1
```

- This affine transformation can also be calculated by the following algorithm:
- Store the multiplicative inverse of the input number in two 8-bit unsigned temporary variables: s and x
- Rotate the value s one bit to the left; if the value of s had a high bit (eight bit from the left) of one, make the low bit of s one; otherwise the low bit of s is zero.
- Exclusive or the value of x with the value of s, storing the value in x
- For three more iterations, repeat steps two and three; steps two and three are done a total of four times.
- The value of ''x'' will now have the transformed value.

Algebraic formulation of AES S-box

- In contrast to the S-boxes in DES, which are apparently "random" substitution, the AES S-box can be defined algebraically.
- AES S-box involves operations in the finite field:

$$F_{2^8} = Z_2[x]/(x^8 + x^4 + x^3 + x + 1).$$

- Let **FieldInv** denote the multiplicative inverse of a field element.
- Let **BinaryToField** convert a byte to a field element; and **FieldToBinary** perform the inverse conversion.

- Rijndael (standardised as AES) uses the characteristic 2 finite field with 256 elements, which can also be called the Galois field **GF**(2^8). It employs the following reducing polynomial for multiplication:

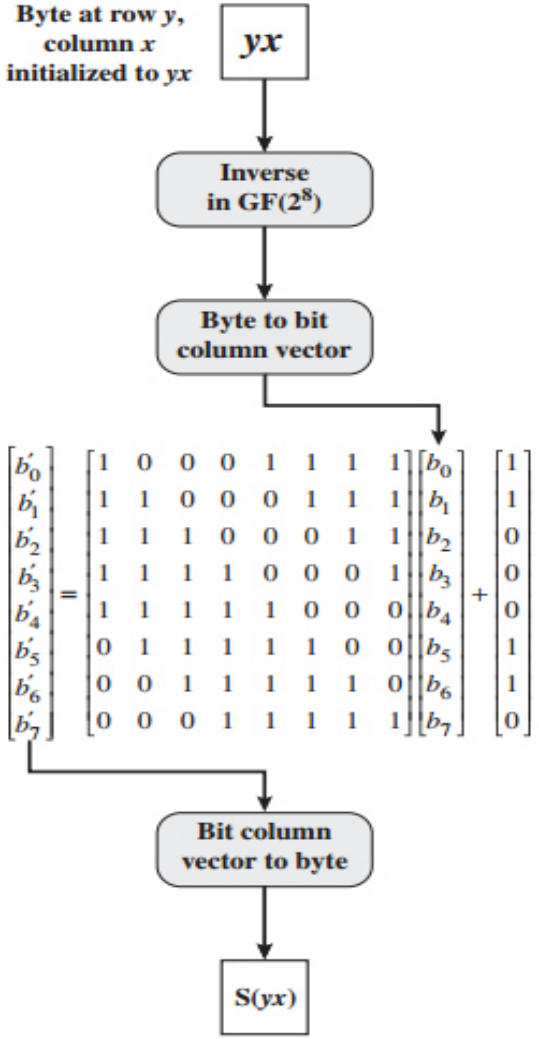
$$x^8 + x^4 + x^3 + x + 1.$$

For example, {53} • {CA} = {01} in Rijndael's field because

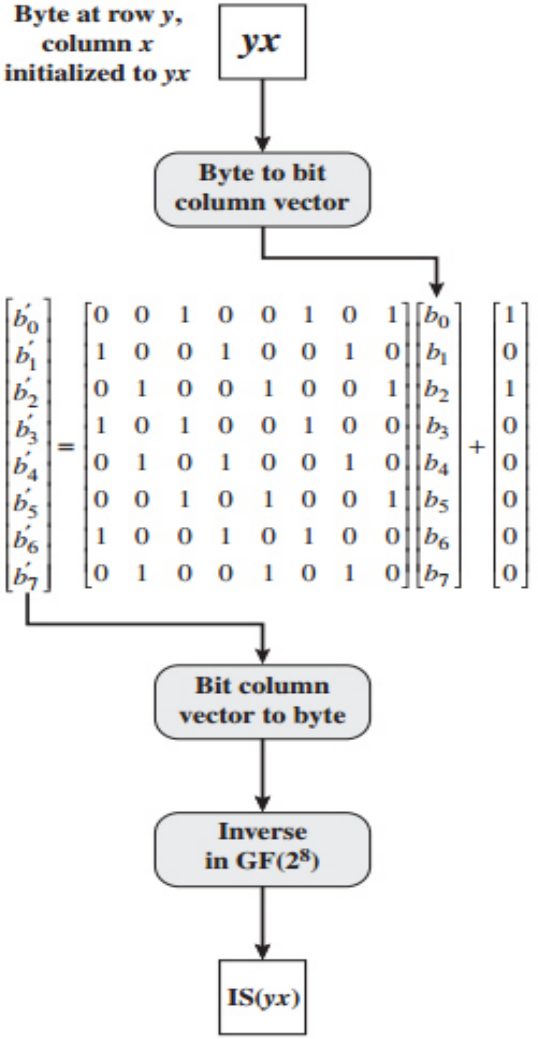
$$(x^6 + x^4 + x + 1)(x^7 + x^6 + x^3 + x)$$
$$= (x^{13} + x^{12} + x^9 + \mathbf{x^7}) + (x^{11} + x^{10} + \mathbf{x^7} + x^5) + (x^8 + \mathbf{x^7} + x^4 + x^2) + (\mathbf{x^7} + x^6 + x^3 + x)$$
$$= x^{13} + x^{12} + x^9 + x^{11} + x^{10} + x^5 + x^8 + x^4 + x^2 + x^6 + x^3 + x$$
$$= x^{13} + x^{12} + x^{11} + x^{10} + x^9 + x^8 + x^6 + x^5 + x^4 + x^3 + x^2 + x$$

and

$$x^{13} + x^{12} + x^{11} + x^{10} + x^9 + x^8 + x^6 + x^5 + x^4 + x^3 + x^2 + x \text{ modulo } x^8 + x^4 + x^3 + x^1 + 1$$
$$= (11111101111110 \bmod 100011011)$$
$$= \{3F7E \bmod 11B\} = \{01\}$$
$$= 1 \text{ (decimal)}$$

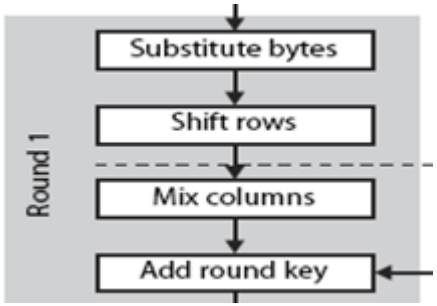


(a) Calculation of byte at row y, column x of S-box



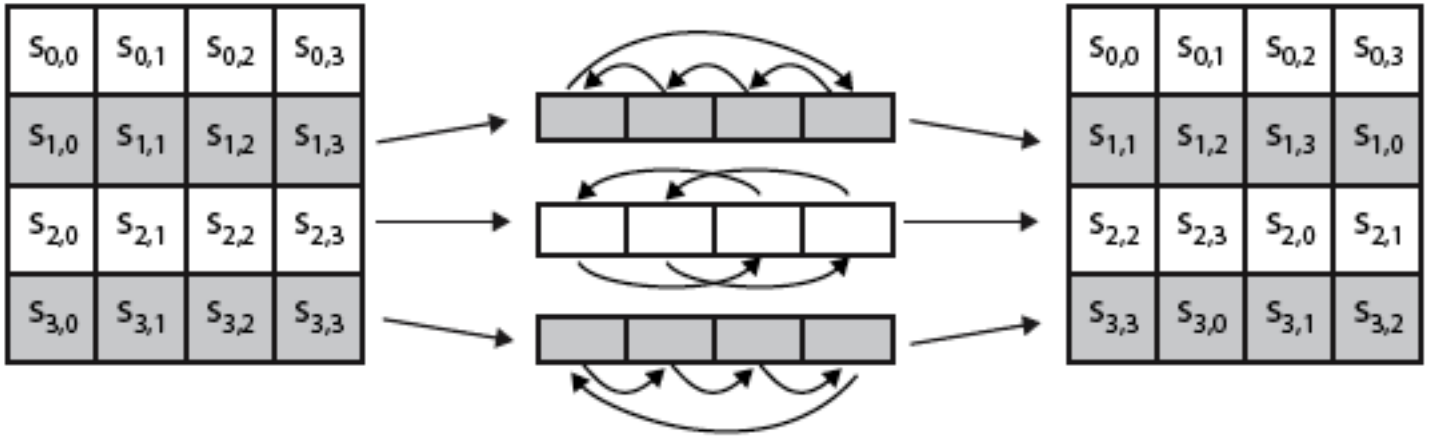
(a) Calculation of byte at row y, column x of IS-box

Shift Row Transformation



- Simple permutation
- It works as follow:
  - The first row of state is not altered.
  - The second row is shifted 1 byte to the left in a circular manner.
  - The third row is shifted 2 bytes to the left in a circular manner.
  - The fourth row is shifted 3 bytes to the left in a circular manner.

Shift Row



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

→

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

- The inverse shift row transformation(known as InvShiftRows) performs these circular shifts in the opposite direction for each of the last three rows(the first row was unaltered to begin with).
- This operation may not appear to do much but if we think about how bytes are ordered within state then it can be seen to have far more of an impact.

Mix Columns

- each column is processed separately
- each byte is replaced by a value dependent on all 4 bytes in the column
- effectively a matrix multiplication in GF(2^8) using prime poly $m(x) = x^8+x^4+x^3+x+1$

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

Mix Column Example

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

→

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

$$(\{02\} \bullet \{87\}) \oplus (\{03\} \bullet \{6E\}) \oplus \{46\} \oplus \{A6\} = \{47\}$$

$$\{87\} \oplus (\{02\} \bullet \{6E\}) \oplus (\{03\} \bullet \{46\}) \oplus \{A6\} = \{37\}$$

$$\{87\} \oplus \{6E\} \oplus (\{02\} \bullet \{46\}) \oplus (\{03\} \bullet \{A6\}) = \{94\}$$

$$(\{03\} \bullet \{87\}) \oplus \{6E\} \oplus \{46\} \oplus (\{02\} \bullet \{A6\}) = \{ED\}$$

Inverse Mix Column

$$\begin{bmatrix} 0E & 0B & 0D & 09 \\ 09 & 0E & 0B & 0D \\ 0D & 09 & 0E & 0B \\ 0B & 0D & 09 & 0E \end{bmatrix} \begin{bmatrix} s_{0,0} & s_{0,1} & s_{0,2} & s_{0,3} \\ s_{1,0} & s_{1,1} & s_{1,2} & s_{1,3} \\ s_{2,0} & s_{2,1} & s_{2,2} & s_{2,3} \\ s_{3,0} & s_{3,1} & s_{3,2} & s_{3,3} \end{bmatrix} = \begin{bmatrix} s'_{0,0} & s'_{0,1} & s'_{0,2} & s'_{0,3} \\ s'_{1,0} & s'_{1,1} & s'_{1,2} & s'_{1,3} \\ s'_{2,0} & s'_{2,1} & s'_{2,2} & s'_{2,3} \\ s'_{3,0} & s'_{3,1} & s'_{3,2} & s'_{3,3} \end{bmatrix}$$

$$\begin{bmatrix} 0E & 0B & 0D & 09 \\ 09 & 0E & 0B & 0D \\ 0D & 09 & 0E & 0B \\ 0B & 0D & 09 & 0E \end{bmatrix} \begin{bmatrix} 02 & 03 & 01 & 01 \\ 01 & 02 & 03 & 01 \\ 01 & 01 & 02 & 03 \\ 03 & 01 & 01 & 02 \end{bmatrix} \begin{bmatrix} s_{0,0} & s_{0,1} & s_{0,2} & s_{0,3} \\ s_{1,0} & s_{1,1} & s_{1,2} & s_{1,3} \\ s_{2,0} & s_{2,1} & s_{2,2} & s_{2,3} \\ s_{3,0} & s_{3,1} & s_{3,2} & s_{3,3} \end{bmatrix} = \begin{bmatrix} s_{0,0} & s_{0,1} & s_{0,2} & s_{0,3} \\ s_{1,0} & s_{1,1} & s_{1,2} & s_{1,3} \\ s_{2,0} & s_{2,1} & s_{2,2} & s_{2,3} \\ s_{3,0} & s_{3,1} & s_{3,2} & s_{3,3} \end{bmatrix}$$

which is equivalent to showing

$$\begin{bmatrix} 0E & 0B & 0D & 09 \\ 09 & 0E & 0B & 0D \\ 0D & 09 & 0E & 0B \\ 0B & 0D & 09 & 0E \end{bmatrix} \begin{bmatrix} 02 & 03 & 01 & 01 \\ 01 & 02 & 03 & 01 \\ 01 & 01 & 02 & 03 \\ 03 & 01 & 01 & 02 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

That is, the inverse transformation matrix times the forward transformation matrix equals the identity matrix. To verify the first column of Equation, we need to show

$$\begin{aligned} (\{0E\} \bullet \{02\}) \oplus \{0B\} \oplus \{0D\} \oplus (\{09\} \bullet \{03\}) &= \{01\} \\ (\{09\} \bullet \{02\}) \oplus \{0E\} \oplus \{0B\} \oplus (\{0D\} \bullet \{03\}) &= \{00\} \\ (\{0D\} \bullet \{02\}) \oplus \{09\} \oplus \{0E\} \oplus (\{0B\} \bullet \{03\}) &= \{00\} \\ (\{0B\} \bullet \{02\}) \oplus \{0D\} \oplus \{09\} \oplus (\{0E\} \bullet \{03\}) &= \{00\} \end{aligned}$$

Add Round Key

- XOR state with 128-bits of the round key
- again processed by column (though effectively a series of byte operations)
- inverse for decryption identical
  - since XOR own inverse, with reversed keys
- designed to be as simple as possible
  - a form of Vernam cipher on expanded key
  - requires other stages for complexity / security

Add Round Key

$s_{0,0}$	$s_{0,1}$	$s_{0,2}$	$s_{0,3}$
$s_{1,0}$	$s_{1,1}$	$s_{1,2}$	$s_{1,3}$
$s_{2,0}$	$s_{2,1}$	$s_{2,2}$	$s_{2,3}$
$s_{3,0}$	$s_{3,1}$	$s_{3,2}$	$s_{3,3}$

$\oplus$

w_i	w_{i+1}	w_{i+2}	w_{i+3}

$=$

$s'_{0,0}$	$s'_{0,1}$	$s'_{0,2}$	$s'_{0,3}$
$s'_{1,0}$	$s'_{1,1}$	$s'_{1,2}$	$s'_{1,3}$
$s'_{2,0}$	$s'_{2,1}$	$s'_{2,2}$	$s'_{2,3}$
$s'_{3,0}$	$s'_{3,1}$	$s'_{3,2}$	$s'_{3,3}$

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

$\oplus$

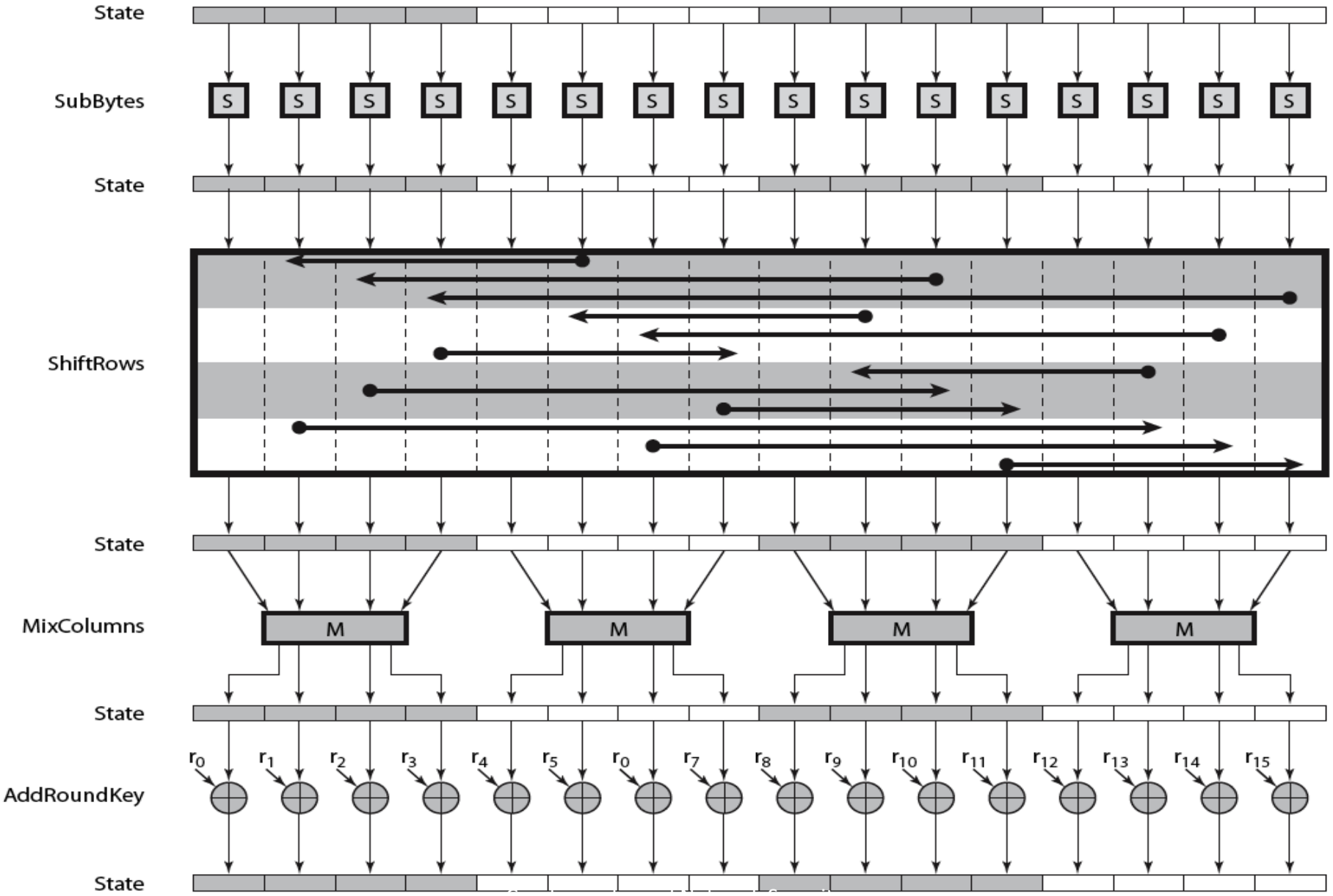
AC	19	28	57
77	FA	D1	5C
66	DC	29	00
F3	21	41	6A

$=$

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

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

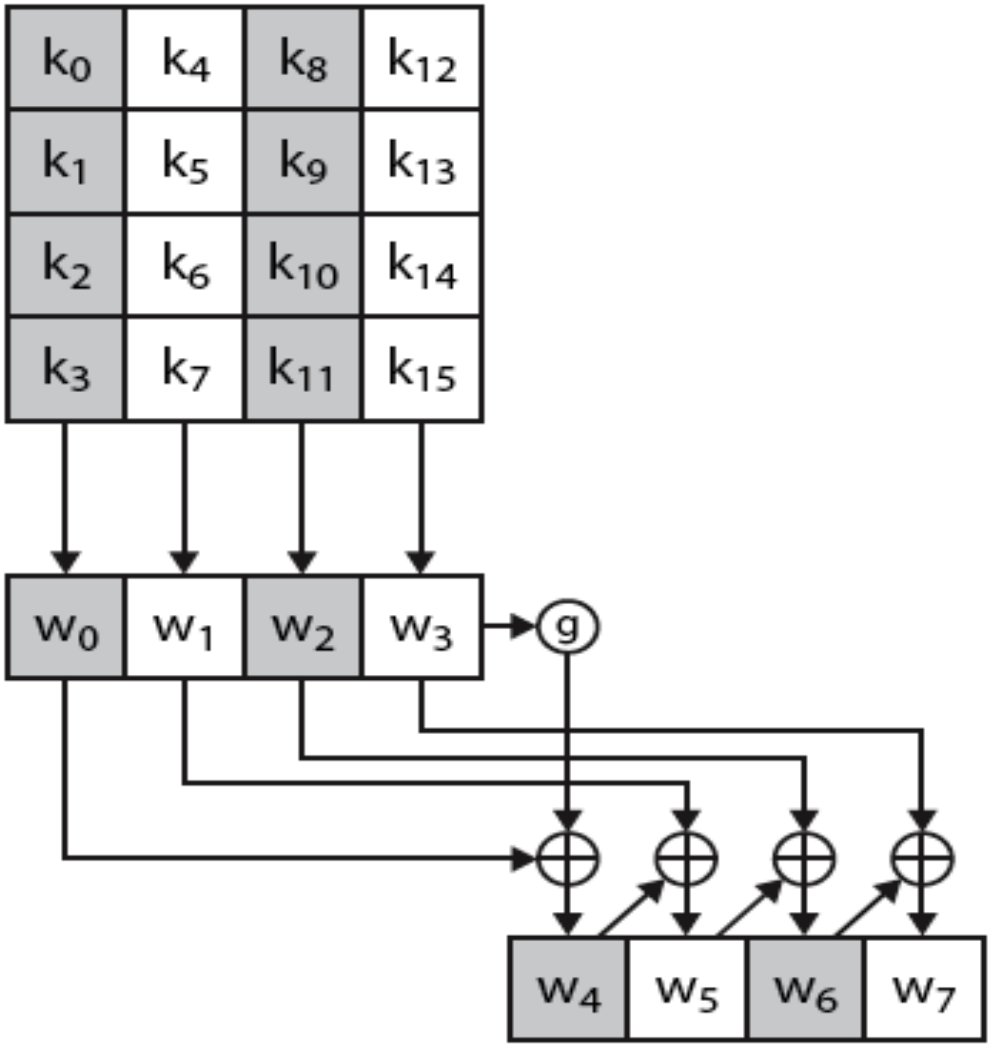
AES Round


State
SubBytes
S
State
ShiftRows
State
MixColumns
M
State
AddRoundKey
r0
r1
r2
r3
r4
r5
r0
r7
r8
r9
r10
r11
r12
r13
r14
r15
State

AES Key Expansion

- takes 128-bit (16-byte) key and expands into array of 44/52/60 32-bit words
- start by copying key into first 4 words
- then loop creating words that depend on values in previous & 4 places back
  - in 3 of 4 cases just XOR these together
  - 1st word in 4 has rotate + S-box + XOR round constant on previous, before XOR 4th back

AES Key Expansion



Function G Consists of the following Subfunctions

1. RotWord performs a one-byte circular left shift on a word. This means that an input word $[B_0, B_1, B_2, B_3]$ is transformed into $[B_1, B_2, B_3, B_0]$.
2. SubWord performs a byte substitution on each byte of its input word, using the S-box (Table 5.2a).
3. The result of steps 1 and 2 is XORed with a round constant, Rcon[j].

j	1	2	3	4	5	6	7	8	9	10
RC[j]	01	02	04	08	10	20	40	80	1B	36

AES Example Key Expansion

Key Words	Auxiliary Function
w0 = 0f 15 71 c9	RotWord(w3)= 7f 67 98 af = x1
w1 = 47 d9 e8 59	SubWord(x1)= d2 85 46 79 = y1
w2 = 0c b7 ad	Rcon(1)= 01 00 00 00
w3 = af 7f 67 98	y1 ⊕ Rcon(1)= d3 85 46 79 = z1
w4 = w0 ⊕ z1 = dc 90 37 b0	RotWord(w7)= 81 15 a7 38 = x2
w5 = w4 ⊕ w1 = 9b 49 df e9	SubWord(x4)= 0c 59 5c 07 = y2
w6 = w5 ⊕ w2 = 97 fe 72 3f	Rcon(2)= 02 00 00 00
w7 = w6 ⊕ w3 = 38 81 15 a7	y2 ⊕ Rcon(2)= 0e 59 5c 07 = z2
w8 = w4 ⊕ z2 = d2 c9 6b b7	RotWord(w11)= ff d3 c6 e6 = x3
w9 = w8 ⊕ w5 = 49 80 b4 5e	SubWord(x2)= 16 66 b4 8e = y3
w10 = w9 ⊕ w6 = de 7e c6 61	Rcon(3)= 04 00 00 00
w11 = w10 ⊕ w7 = e6 ff d3 c6	y3 ⊕ Rcon(3)= 12 66 b4 8e = z3
w12 = w8 ⊕ z3 = c0 af df 39	RotWord(w15)= ae 7e c0 b1 = x4
w13 = w12 ⊕ w9 = 89 2f 6b 67	SubWord(x3)= e4 f3 ba c8 = y4
w14 = w13 ⊕ w10 = 57 51 ad 06	Rcon(4)= 08 00 00 00
w15 = w14 ⊕ w11 = b1 ae 7e c0	y4 ⊕ Rcon(4)= ec f3 ba c8 = 4
w16 = w12 ⊕ z4 = 2c 5c 65 f1	RotWord(w19)= 8c dd 50 43 = x5
w17 = w16 ⊕ w13 = a5 73 0e 96	SubWord(x4)= 64 c1 53 1a = y5
w18 = w17 ⊕ w14 = f2 22 a3 90	Rcon(5)= 10 00 00 00
w19 = w18 ⊕ w15 = 43 8c dd 50	y5 ⊕ Rcon(5)= 74 c1 53 1a = z5
w20 = w16 ⊕ z5 = 58 9d 36 eb	RotWord(w23)= 40 46 bd 4c = x6
w21 = w20 ⊕ w17 = fd ee 38 7d	SubWord(x5)= 09 5a 7a 29 = y6
w22 = w21 ⊕ w18 = 0f cc 9b ed	Rcon(6)= 20 00 00 00
w23 = w22 ⊕ w19 = 4c 40 46 bd	y6 ⊕ Rcon(6)= 29 5a 7a 29 = z6
w24 = w20 ⊕ z6 = 71 c7 4c c2	RotWord(w27)= a5 a9 ef cf = x7
w25 = w24 ⊕ w21 = 8c 29 74 bf	SubWord(x6)= 06 d3 df 8a = y7
w26 = w25 ⊕ w22 = 83 e5 ef 52	Rcon(7)= 40 00 00 00
w27 = w26 ⊕ w23 = cf a5 a9 ef	y7 ⊕ Rcon(7)= 46 d3 df 8a = z7
w28 = w24 ⊕ z7 = 37 14 93 48	RotWord(w31)= 7d a1 4a f7 = x8
w29 = w28 ⊕ w25 = bb 3d e7 f7	SubWord(x7)= ff 32 d6 68 = y8
w30 = w29 ⊕ w26 = 38 d8 08 a5	Rcon(8)= 80 00 00 00
w31 = w30 ⊕ w27 = f7 7d a1 4a	y8 ⊕ Rcon(8)= 7f 32 d6 68 = z8
w32 = w28 ⊕ z8 = 48 26 45 20	RotWord(w35)= be 0b 38 3c = x9
w33 = w32 ⊕ w29 = f3 1b a2 d7	SubWord(x8)= ae 2b 07 eb = y9
w34 = w33 ⊕ w30 = cb c3 aa 72	Rcon(9)= 1B 00 00 00
w35 = w34 ⊕ w32 = 3c be 0b 38	y9 ⊕ Rcon(9)= b5 2b 07 eb = z9
w36 = w32 ⊕ z9 = fd 0d 42 cb	RotWord(w39)= 6b 41 56 f9 = x10
w37 = w36 ⊕ w33 = 0e 16 e0 1c	SubWord(x9)= 7f 83 b1 99 = y10
w38 = w37 ⊕ w34 = c5 d5 4a 6e	Rcon(10)= 36 00 00 00
w39 = w38 ⊕ w35 = f9 6b 41 56	y10 ⊕ Rcon(10)= 49 83 b1 99 = z10
w40 = w36 ⊕ z10 = b4 8e f3 52	
w41 = w40 ⊕ w37 = ba 98 13 4e	
w42 = w41 ⊕ w38 = 7f 4d 59 20	
w43 = w42 ⊕ w39 = 86 26 18 76	

Key Words	Auxiliary Function
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w1 = 47 d9 e8 59	SubWord(x1)= d2 85 46 79 = y1
w2 = 0c b7 ad	Rcon(1)= 01 00 00 00
w3 = af 7f 67 98	y1 ⊕ Rcon(1)= d3 85 46 79 = z1
w4 = w0 ⊕ z1 = dc 90 37 b0	RotWord(w7)= 81 15 a7 38 = x2
w5 = w4 ⊕ w1 = 9b 49 df e9	SubWord(x4)= 0c 59 5c 07 = y2
w6 = w5 ⊕ w2 = 97 fe 72 3f	Rcon(2)= 02 00 00 00
w7 = w6 ⊕ w3 = 38 81 15 a7	y2 ⊕ Rcon(2)= 0e 59 5c 07 = z2

1. RotWord performs a one-byte circular left shift on a word. This means that an input word $[B_0, B_1, B_2, B_3]$ is transformed into $[B_1, B_2, B_3, B_0]$.
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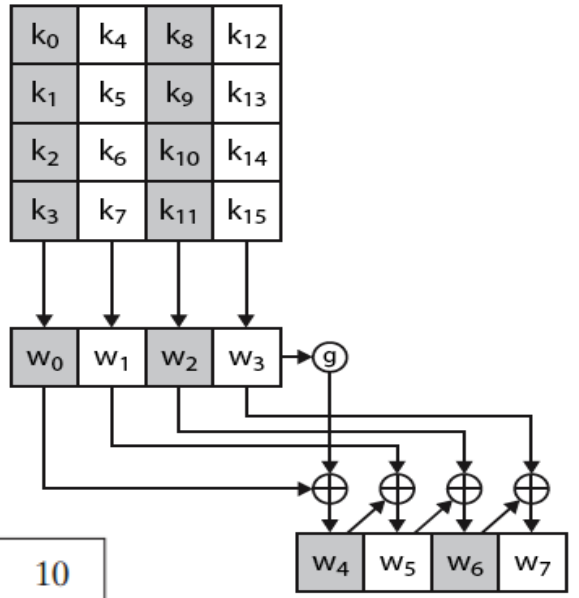

j	1	2	3	4	5	6	7	8	9	10
RC[j]	01	02	04	08	10	20	40	80	1B	36

Key Expansion Rationale

- designed to resist known attacks
- design criteria included
  - knowing part key insufficient to find many more
  - invertible transformation
  - fast on wide range of CPU's
  - use round constants to break symmetry
  - diffuse key bits into round keys
  - enough non-linearity to hinder analysis
  - simplicity of description

AES Example Encryption

Start of round	After SubBytes	After ShiftRows	After MixColumns	Round Key
01 89 fe 76 23 ab dc 54 45 cd ba 32 67 ef 98 10				0f 47 0c af 15 d9 b7 7f 71 e8 ad 67 c9 59 d6 98
0e ce f2 d9 36 72 6b 2b 34 25 17 55 ae b6 4e 88	ab 8b 89 35 05 40 7f f1 18 3f f0 fc e4 4e 2f c4	ab 8b 89 35 40 7f f1 05 f0 fc 18 3f c4 e4 4e 2f	b9 94 57 75 e4 8e 16 51 47 20 9a 3f c5 d6 f5 3b	dc 9b 97 38 90 49 fe 81 37 df 72 15 b0 e9 3f a7
65 0f c0 4d 74 c7 e8 d0 70 ff e8 2a 75 3f ca 9c	4d 76 ba e3 92 c6 9b 70 51 16 9b e5 9d 75 74 de	4d 76 ba e3 c6 9b 70 92 9b e5 51 16 de 9d 75 74	8e 22 db 12 b2 f2 dc 92 df 80 f7 c1 2d c5 1e 52	d2 49 de e6 c9 80 7e ff 6b b4 c6 d3 b7 5e 61 c6
5c 6b 05 f4 7b 72 a2 6d b4 34 31 12 9a 9b 7f 94	4a 7f 6b bf 21 40 3a 3c 8d 18 c7 c9 b8 14 d2 22	4a 7f 6b bf 40 3a 3c 21 c7 c9 8d 18 22 b8 14 d2	b1 c1 0b cc ba f3 8b 07 f9 1f 6a c3 1d 19 24 5c	c0 89 57 b1 af 2f 51 ae df 6b ad 7e 39 67 06 c0
71 48 5c 7d 15 dc da a9 26 74 c7 bd 24 7e 22 9c	a3 52 4a ff 59 86 57 d3 f7 92 c6 7a 36 f3 93 de	a3 52 4a ff 86 57 d3 59 c6 7a f7 92 de 36 f3 93	d4 11 fe 0f 3b 44 06 73 cb ab 62 37 19 b7 07 ec	2c a5 f2 43 5c 73 22 8c 65 0e a3 dd f1 96 90 50
f8 b4 0c 4c 67 37 24 ff ae a5 c1 ea e8 21 97 bc	41 8d fe 29 85 9a 36 16 e4 06 78 87 9b fd 88 65	41 8d fe 29 9a 36 16 85 78 87 e4 06 65 9b fd 88	2a 47 c4 48 83 e8 18 ba 84 18 27 23 eb 10 0a f3	58 fd 0f 4c 9d ee cc 40 36 38 9b 46 eb 7d ed bd
72 ba cb 04 1e 06 d4 fa b2 20 bc 65 00 6d e7 4e	40 f4 1f f2 72 6f 48 2d 37 b7 65 4d 63 3c 94 2f	40 f4 1f f2 6f 48 2d 72 65 4d 37 b7 2f 63 3c 94	7b 05 42 4a 1e d0 20 40 94 83 18 52 94 c4 43 fb	71 8c 83 cf c7 29 e5 a5 4c 74 ef a9 c2 bf 52 ef
0a 89 c1 85 d9 f9 c5 e5 d8 f7 f7 fb 56 7b 11 14	67 a7 78 97 35 99 a6 d9 61 68 68 0f b1 21 82 fa	67 a7 78 97 99 a6 d9 35 68 0f 61 68 fa b1 21 82	ec 1a c0 80 0c 50 53 c7 3b d7 00 ef b7 22 72 e0	37 bb 38 f7 14 3d d8 7d 93 e7 08 a1 48 f7 a5 4a
db a1 f8 77 18 6d 8b ba a8 30 08 4e ff d5 d7 aa	b9 32 41 f5 ad 3c 3d f4 c2 04 30 2f 16 03 0e ac	b9 32 41 f5 3c 3d f4 ad 30 2f c2 04 ac 16 03 0e	b1 1a 44 17 3d 2f ec b6 0a 6b 2f 42 9f 68 f3 b1	48 f3 cb 3c 26 1b c3 be 45 a2 aa 0b 20 d7 72 38
f9 e9 8f 2b 1b 34 2f 08 4f c9 85 49 bf bf 81 89	99 1e 73 f1 af 18 15 30 84 dd 97 3b 08 08 0c a7	99 1e 73 f1 18 15 30 af 97 3b 84 dd a7 08 08 0c	31 30 3a c2 ac 71 8c c4 46 65 48 eb 6a 1c 31 62	fd 0e c5 f9 0d 16 d5 6b 42 e0 4a 41 cb 1c 6e 56
cc 3e ff 3b a1 67 59 af 04 85 02 aa a1 00 5f 34	4b b2 16 e2 32 85 cb 79 f2 97 77 ac 32 63 cf 18	4b b2 16 e2 85 cb 79 32 77 ac f2 97 18 32 63 cf	4b 86 8a 36 b1 cb 27 5a fb f2 f2 af cc 5a 5b cf	b4 8e f3 52 ba 98 13 4e 7f 4d 59 20 86 26 18 76
ff 08 69 64 0b 53 34 14 84 bf ab 8f 4a 7c 43 b9				

AES Decryption

- AES decryption is not identical to encryption since steps done in reverse
- but can define an equivalent inverse cipher with steps as for encryption
  - but using inverses of each step
  - with a different key schedule
- works since result is unchanged when
  - swap byte substitution & shift rows
  - swap mix columns & add (tweaked) round key

AES Decryption