RAMAIAH Institute of Technology

M.S. Ramaiah Institute of Technology
(Autonomous Institute, Affiliated to VTU)
Department of Computer Science and Engineering

Course Name: Cryptography and Network Security

Course Code - CSE643

Credits - 3:0:0

UNIT -2

Term: March 2022 – July 2022

Prepared by: Dr. Sangeetha. V
Assistant Professor

RAMAIAH
Institute of Technology

Unit II (Text1)

Traditional Symmetric-Key Ciphers: (Chapter 3)

- Introduction
- Substitution Ciphers
- Trans positional Ciphers
- Stream and Block Ciphers

Data Encryption Standard (DES): (Chapter 6)

- Introduction
- DES Structure
- DES Analysis
- Security of DES

Advanced Encryption Standard(AES): (Chapter 7)

- Introduction
- Transformations
- Key Expansion
- The AES Ciphers
- Examples
- Analysis of AES.

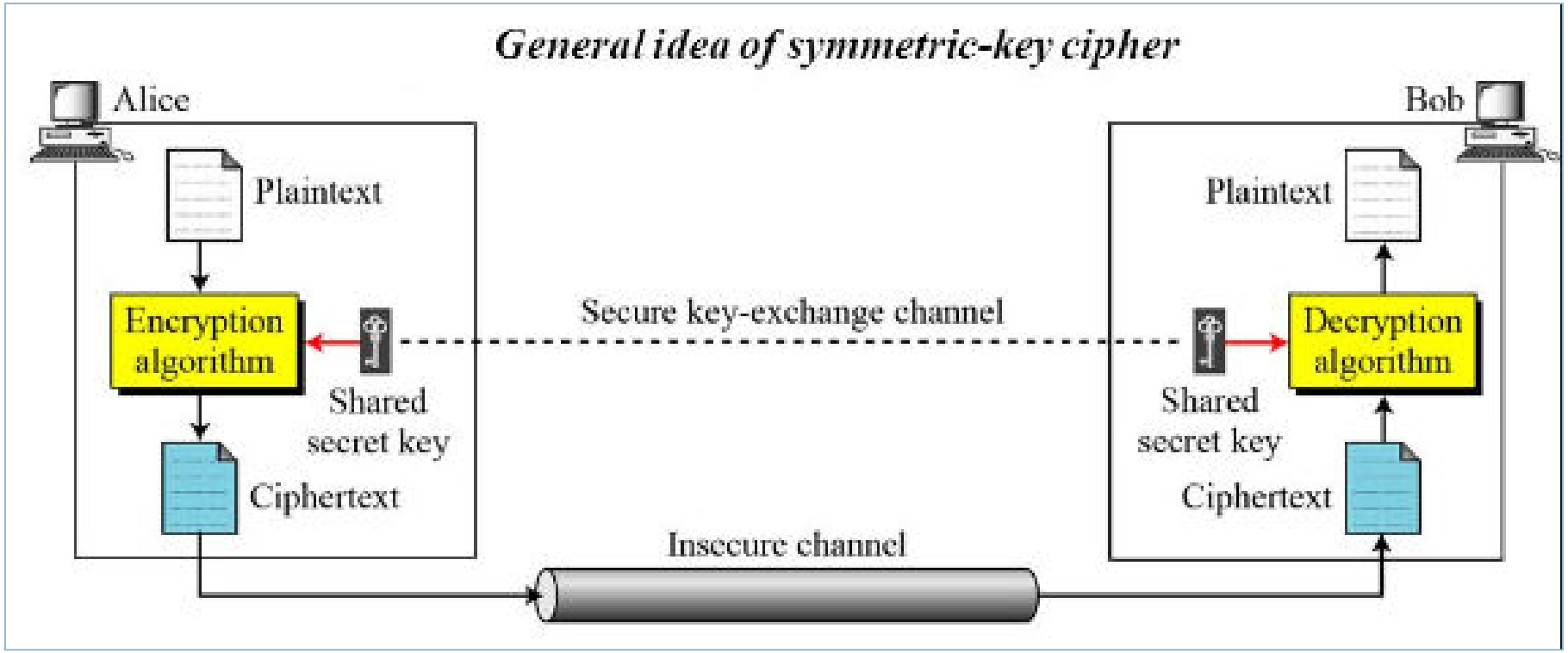
Introduction -Symmetric Key ciphers

Traditional Symmetric-key ciphers are not used today, but we study for several reason:

1. They are simpler than modern ciphers and easier to understand
2. They show basic foundation of cryptography and encipherment.
3. They provide rationale for using modern ciphers, traditional ciphers can be easily attacked using computer

Introduction -Symmetric Key ciphers

Figure shows the general idea behind a symmetric key cipher



Introduction -Symmetric Key ciphers

The original message from Alice to Bob is called plaintext;

The message that is sent through the channel is called the ciphertext.

To create the ciphertext from the plaintext, Alice uses an encryption algorithm and a shared secret key.

To create the plaintext from ciphertext, Bob uses a decryption algorithm and the same secret key.

Introduction -Symmetric Key ciphers

We refer to encryption and decryption algorithms as Ciphers

A Key is a set of values(Numbers) that the cipher operates on

Introduction -Symmetric Key ciphers

If P is the plaintext, C is the ciphertext, and K is the key,

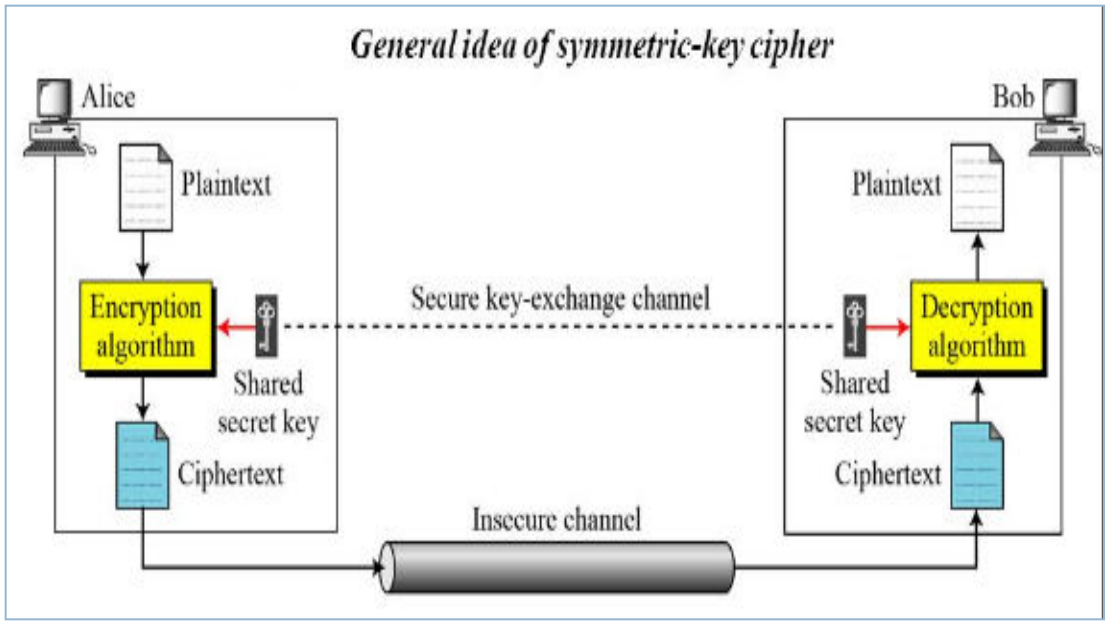
Encryption: $C = E_k(P)$ Decryption: $P = D_k(C)$

In which, $D_k(E_k(x)) = E_k(D_k(x)) = x$

We assume that Bob creates P_1; we prove that $P_1 = P$:

Alice: $C = E_k(P)$

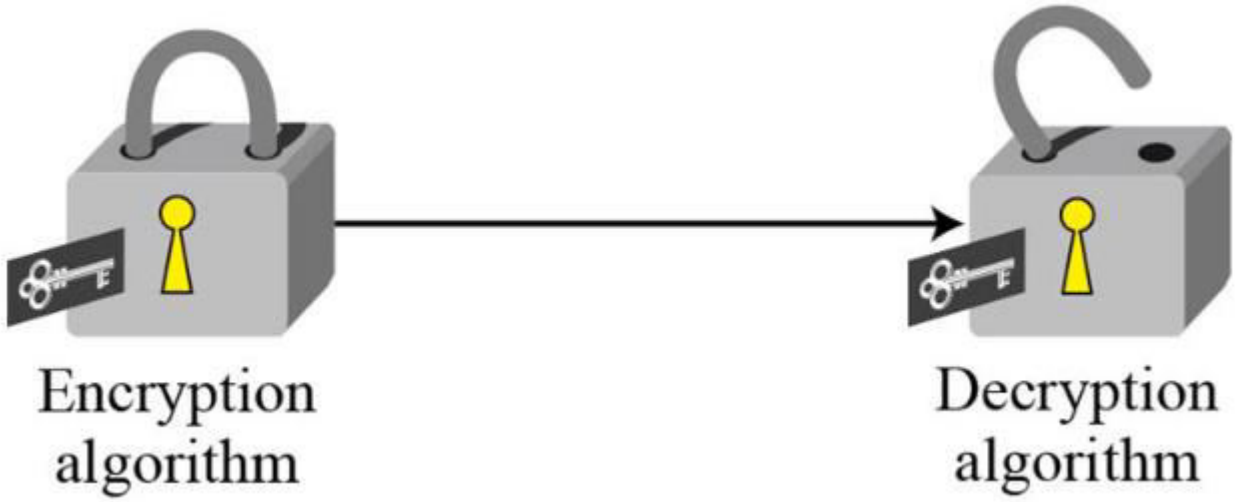
Bob: $P_1 = D_k(C) = D_k(E_k(P)) = P$



Introduction -Symmetric Key ciphers

Figure shows Locking and unlocking with the same key.

Alice and Bob meet once and exchange the key personally.



Introduction -Symmetric Key ciphers

Kerckhoff's Principle

- According to Kerckhoff's principle, it is better to make encryption and decryption public, but keep the shared key secret.
- Based on Kerckhoff's principle, one should always assume that the adversary, Eve, knows the encryption/decryption algorithm.
- The resistance of the cipher to attack must be based only on the secrecy of the key.

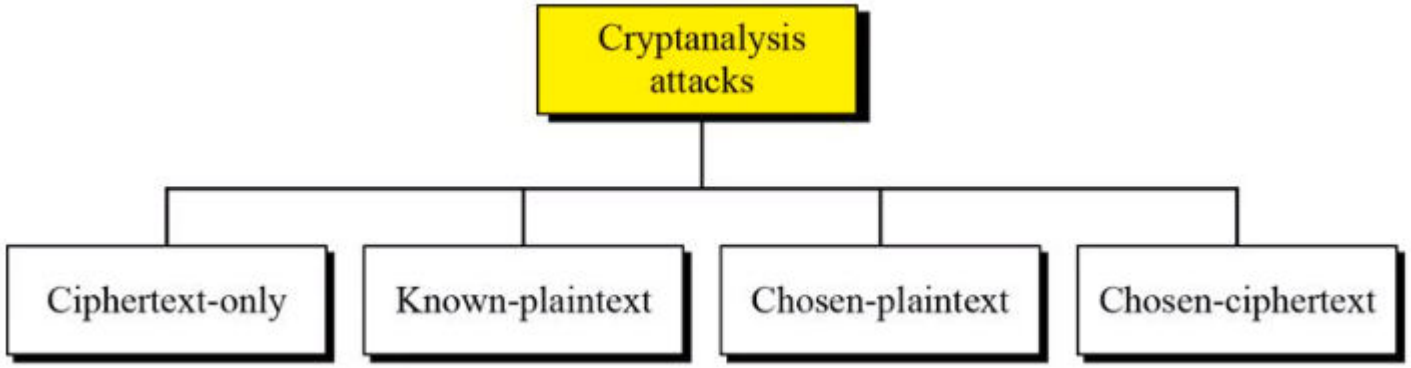
Introduction -Symmetric Key ciphers

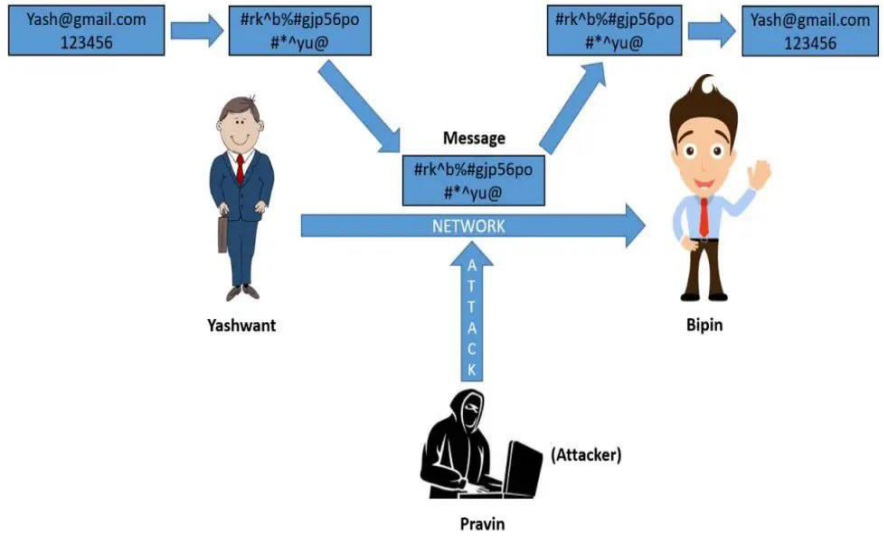
Cryptanalysis

Cryptography is the science and art of creating secret codes.

Cryptanalysis is the science and art of breaking those codes.

Figure shows Cryptanalysis attack froms

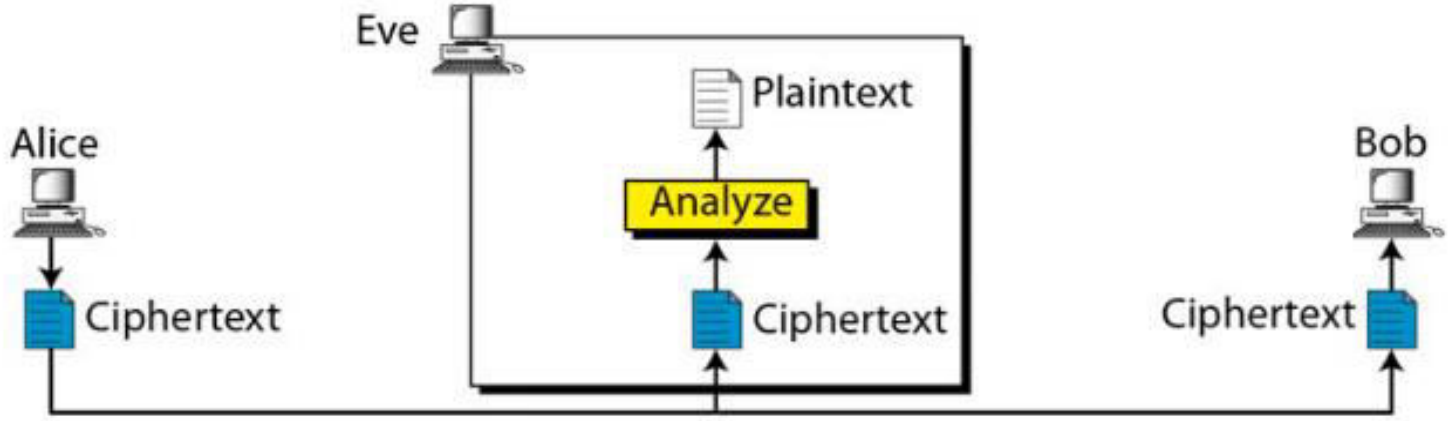




Introduction -Symmetric Key ciphers

Cryptanalysis - Ciphertext-only attack

- Eve has access to only some ciphertext, then finds the key and plaintext.
- Assume eve knows the encryption algorithm



Introduction -Symmetric Key ciphers

Cryptanalysis - Ciphertext-only attack

Various methods can be used in Ciphertext-only attack

1. Brute-Force attack: exhaustive key search attack
2. Statistical attack: benefit from inherent characteristics of the plaintext language. E.g. E is the most frequently used letter.
3. Pattern attack: discover pattern in ciphertext.

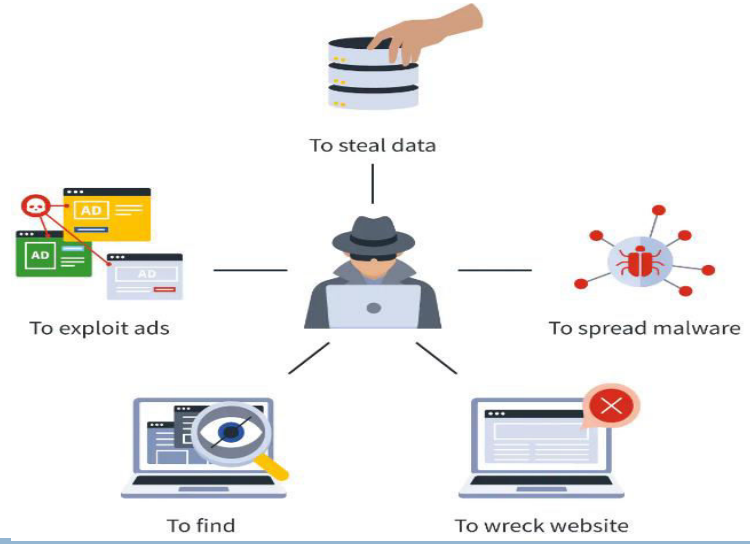
Introduction -Symmetric Key ciphers

1. Brute-Force attack:

If the key is 8 bits long, then the number of possible keys is 2^8 = 256keys

Often target popular platforms where many users store data.

Email domains, online tax services, or food apps could be likely targets.



Introduction -Symmetric Key ciphers

2. Statistical attack:

It is the study of the frequency of letters or groups of letters in a ciphertext.

Benefit from inherent characteristics of the plaintext language. E.g. E is the most frequently used letter.

Statistical attacks target vulnerabilities in the operating systems or hardware hosting the functional cryptography tool.

Introduction -Symmetric Key ciphers

2. Statistical attack:

For example, Database containing employee details may be used by others to calculate the average salary of employees based on particular criteria.

If a user discovered a criterion which only holds for one employee, and uses this information to find the average salary of all employees, then the employee's salary could be easily discovered.

Introduction -Symmetric Key ciphers

3. Pattern attack:

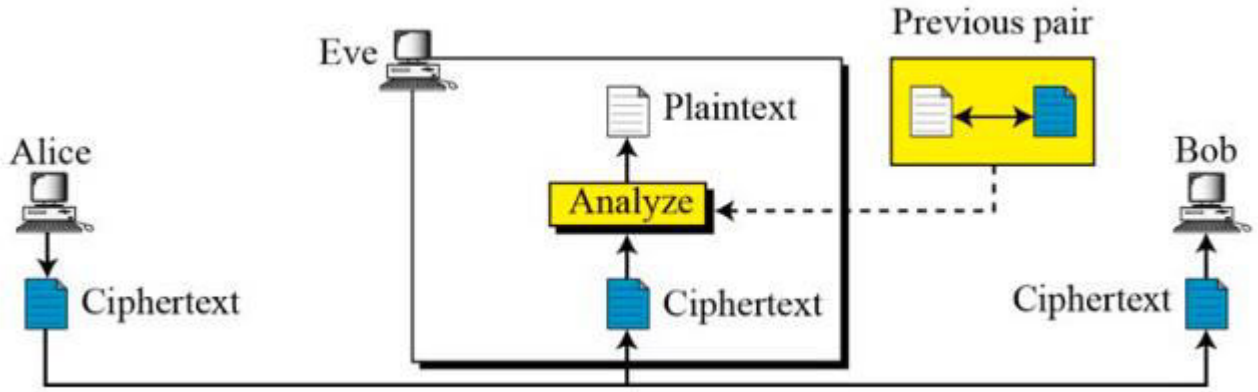
Some ciphers may hide the characteristics of the language, but create some patterns in the ciphertext

Cryptanalyst will use pattern to break the cipher

Introduction -Symmetric Key ciphers

Cryptanalysis -Known-Plaintext Attack

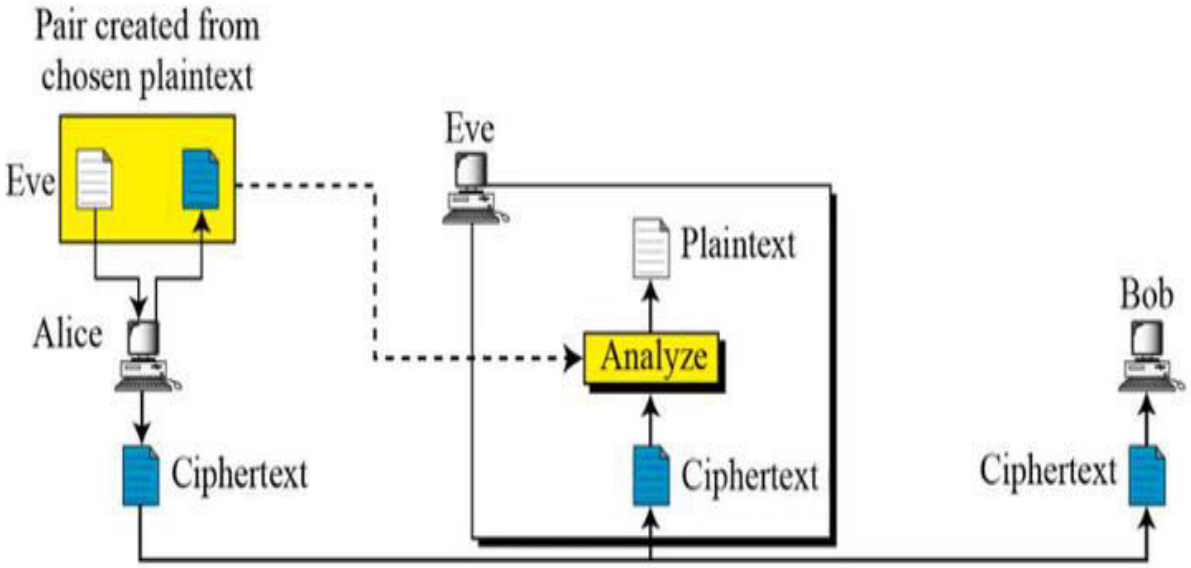
- Eve has access to some plaintext/ciphertext pairs in addition to the intercepted ciphertext that he/she wants to break.
- Plaintext/Ciphertext pairs have been collected earlier.



Introduction -Symmetric Key ciphers

Cryptanalysis -Chosen-Plaintext Attack

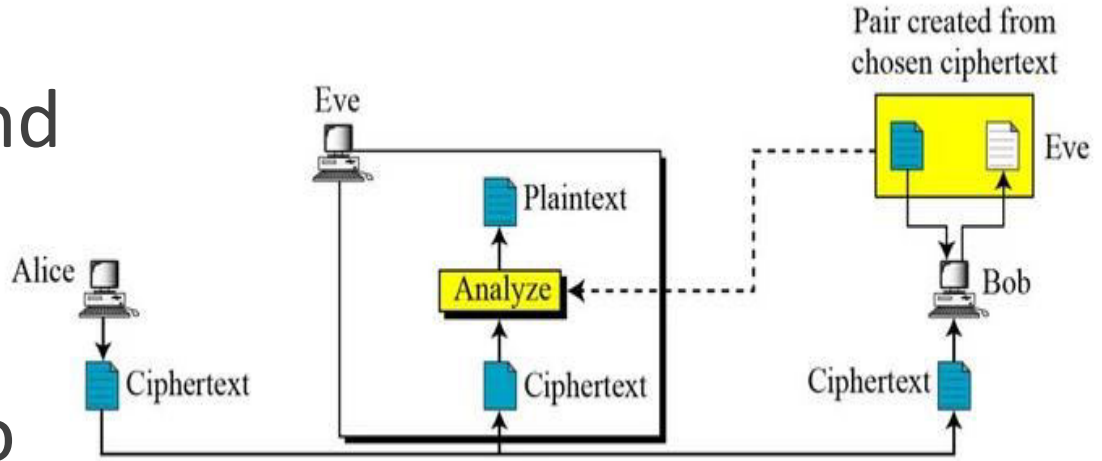
- Eve has access to Alice computer
- Cryptanalyst chose some plaintext and intercept the created plaintext.
- Observing the Plaintext/ciphertext gives Eve a strong foothold into the inner workings of the algorithm and secret key.



Introduction -Symmetric Key ciphers

Cryptanalysis -Chosen-Ciphertext Attack

- Eve has access to Bob computer
- Cryptanalyst chose some ciphertext and decrypts to form the pair plaintext/ciphertext.
- Cryptanalyst is not necessarily trying to find the plaintext, but rather they are trying to decipher the algorithm and secret key used to encrypt the plaintext. .



Introduction -Symmetric Key ciphers

Type of Attack	Known to cryptanalyst
Ciphertext Only	★ Encryption Algorithm ★ Ciphertext
Known Plaintext	★ Encryption Algorithm ★ Ciphertext ★ One or more PT-CT pairs formed with secret key
Chosen Plaintext	★ Encryption Algorithm ★ Ciphertext ★ PT message chosen by cryptanalyst, together with its CT generated with the secret key
Chosen Ciphertext	★ Encryption Algorithm ★ Ciphertext ★ CT chosen by cryptanalyst, together with its corresponding decrypted PT generated with the secret key

Substitution Ciphers

A substitution cipher replaces one symbol with another.

If the symbols in the plaint text are alphabetic characters, replaces one character with another.

Substitution ciphers can be categorized as either

a. Monoalphabetic ciphers
b. Polyalphabetic ciphers

Substitution Ciphers

Monoalphabetic ciphers

a. Additive cipher(Shift cipher/Ceasar cipher)
b. Multiplicative ciphers
c. Affine cipher

Substitution Ciphers

Monoalphabetic ciphers

A Character in the plaint text is changed to the same character in the ciphertext regardless of its position in the plaintext

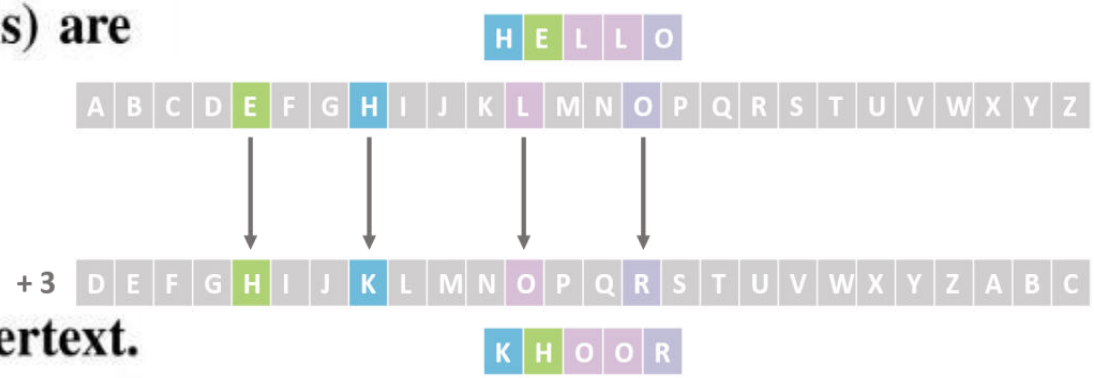
The relationship between a symbol in the plaintext to a symbol in the ciphertext is always one-to-one.

Substitution Ciphers

Monoalphabetic ciphers

The following shows a plaintext and its corresponding ciphertext. The cipher is probably monoalphabetic because both *l*'s (els) are encrypted as *O*'s.

Plaintext: hello **Ciphertext:** KHOOR



The following shows a plaintext and its corresponding ciphertext. The cipher is not monoalphabetic because each *l* (el) is encrypted by a different character.

Plaintext: hello **Ciphertext:** JKQNZ

Substitution Ciphers

Monoalphabetic ciphers – Additive cipher

The simplest monoalphabetic cipher is the additive cipher.

This cipher is sometimes called a shift cipher/Caesar cipher, but the term additive cipher better reveals its mathematical nature.

To apply mathematical operations on PT/CT, assign numerical values to each letter

Each character is assigned an integer in Z_{26}

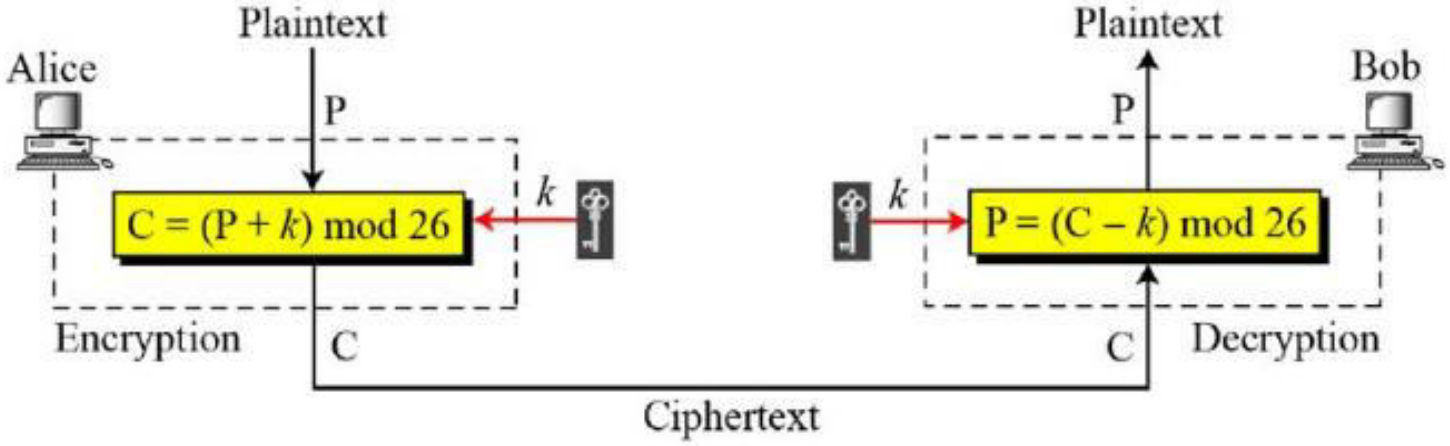
Plaintext and ciphertext in Z_{26}

Plaintext →	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z
Ciphertext →	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
Value →	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25

Substitution Ciphers

Monoalphabetic ciphers – Additive cipher

Plaintext →	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z
Ciphertext →	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
Value →	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25



When the cipher is additive, the plaintext, ciphertext, and key are integers in Z_{26}.

Substitution Ciphers

Monoalphabetic ciphers – Additive cipher

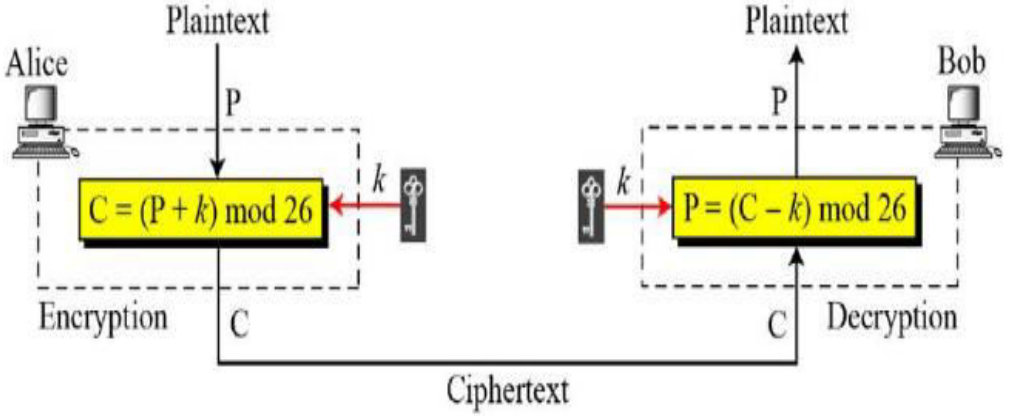
Plaintext →	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z
Ciphertext →	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
Value →	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25

Use the additive cipher with key = 15 to encrypt the message "hello".

Solution

We apply the encryption algorithm to the plaintext, character by character:

Plaintext: h → 07	Encryption: (07 + 15) mod 26	Ciphertext: 22 → W
Plaintext: e → 04	Encryption: (04 + 15) mod 26	Ciphertext: 19 → T
Plaintext: l → 11	Encryption: (11 + 15) mod 26	Ciphertext: 00 → A
Plaintext: l → 11	Encryption: (11 + 15) mod 26	Ciphertext: 00 → A
Plaintext: o → 14	Encryption: (14 + 15) mod 26	Ciphertext: 03 → D



Substitution Ciphers

Monoalphabetic ciphers – Additive cipher

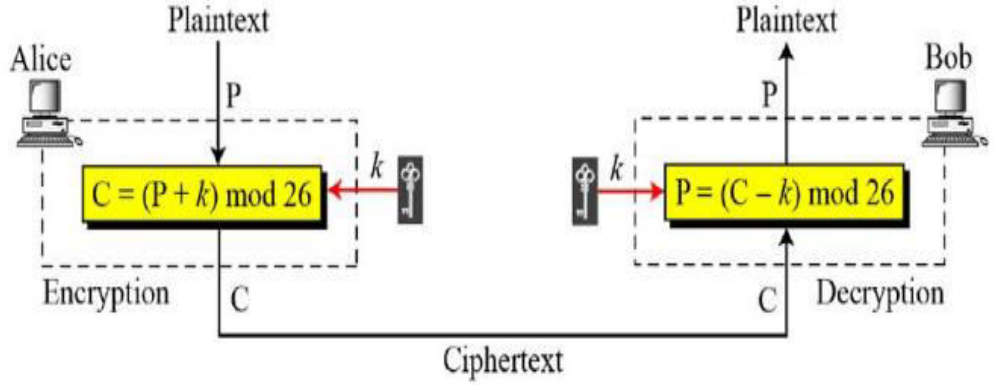
Plaintext →	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z
Ciphertext →	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
Value →	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25

Use the additive cipher with key = 15 to decrypt the message "WTAAD".

Solution

We apply the decryption algorithm to the plaintext character by character:

Ciphertext: W → 22	Decryption: (22 – 15) mod 26	Plaintext: 07 → h
Ciphertext: T → 19	Decryption: (19 – 15) mod 26	Plaintext: 04 → e
Ciphertext: A → 00	Decryption: (00 – 15) mod 26	Plaintext: 11 → l
Ciphertext: A → 00	Decryption: (00 – 15) mod 26	Plaintext: 11 → l
Ciphertext: D → 03	Decryption: (03 – 15) mod 26	Plaintext: 14 → o

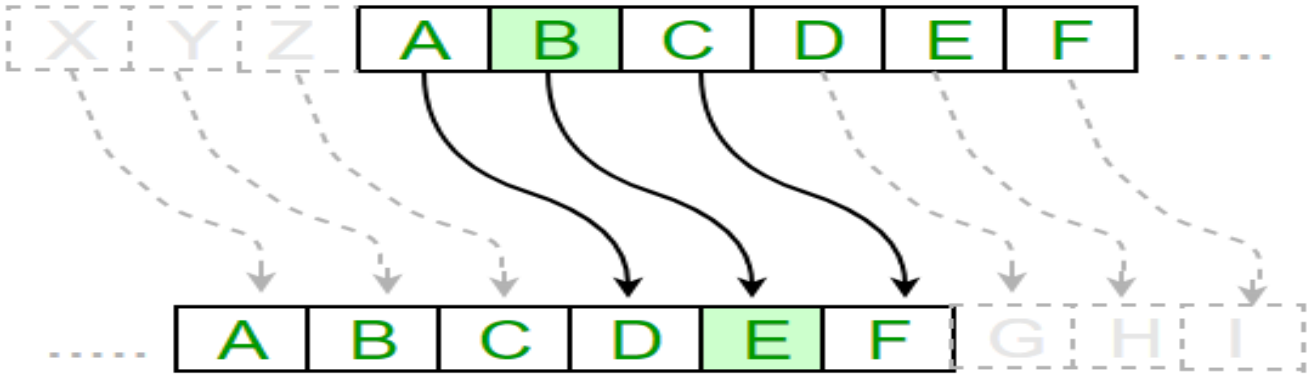


Substitution Ciphers

Monoalphabetic ciphers – Additive cipher

Shift Cipher

A **shift cipher** involves replacing each letter in the message by a letter that is some fixed number of positions further along in the alphabet.



Substitution Ciphers

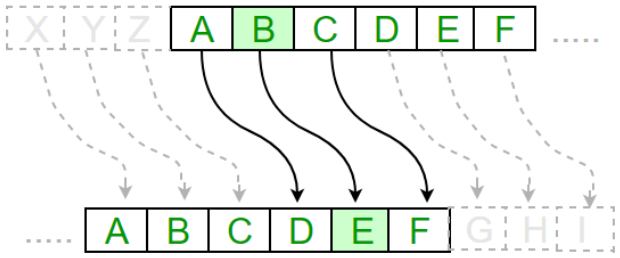
Monoalphabetic ciphers – Additive cipher

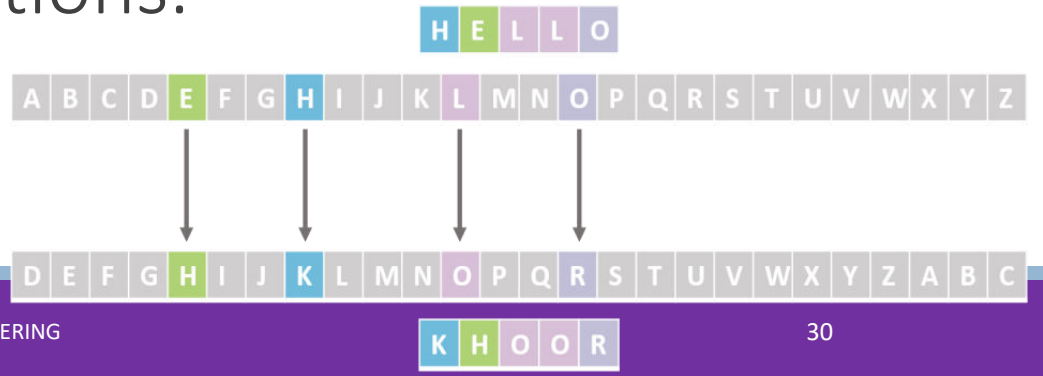
Caesar Cipher

Caesar used an additive cipher to communicate with his officers.

For this reason, additive ciphers are sometimes referred to as the Caesar cipher.

Caesar used a key of 3 for his communications.



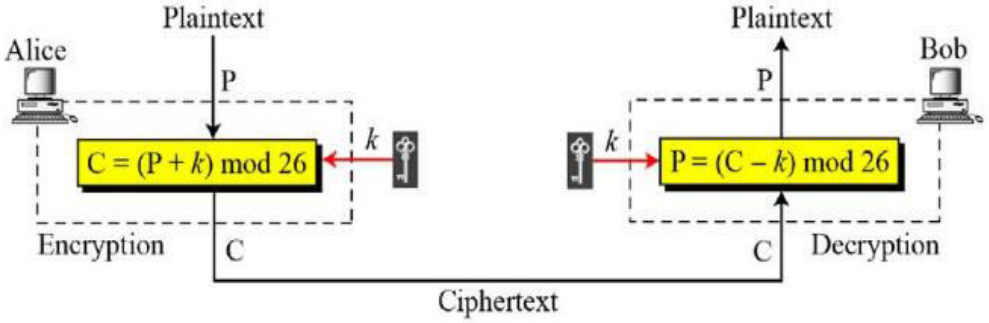


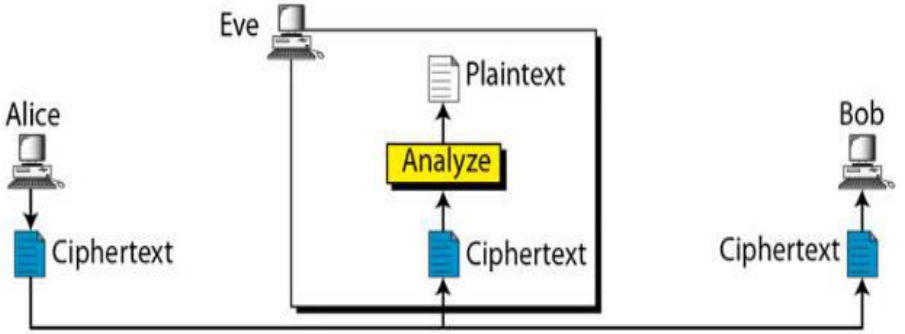
Substitution Ciphers

Monoalphabetic ciphers – Additive cipher

Cryptanalysis -Vulnerable to cipher-text only attack (Brute force attack)

Eve has intercepted the ciphertext "UVACLYFZLJBYL". Show how she can use a brute-force attack to break the cipher.





Plaintext →	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z
Ciphertext →	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
Value →	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25

Eve has intercepted the ciphertext "UVACLYFZLJBYL". Show how she can use a brute-force attack to break the cipher.

Solution

Eve tries keys from 1 to 7. With a key of 7, the plaintext is "not very secure", which makes sense.

Ciphertext: UVACLYFZLJBYL

K = 1 → **Plaintext:** tuzbkxeykiaxk
K = 2 → **Plaintext:** styajwdxjhzwj
K = 3 → **Plaintext:** rsxzivcwigyvi
K = 4 → **Plaintext:** qrwyhubvhfxuh
K = 5 → **Plaintext:** pqvxgtaugewtg
K = 6 → **Plaintext:** opuwfsztfdvsf
K = 7 → **Plaintext:** notverysecure

Substitution Ciphers

Monoalphabetic ciphers – Additive cipher

Cryptanalysis

- Vulnerable to cipher-text only attack (Statistical attack)

Frequency of characters in English

Letter	*Frequency*	*Letter*	*Frequency*	*Letter*	*Frequency*	*Letter*	*Frequency*
E	12.7	H	6.1	W	2.3	K	0.08
T	9.1	R	6.0	F	2.2	J	0.02
A	8.2	D	4.3	G	2.0	Q	0.01
O	7.5	L	4.0	Y	2.0	X	0.01
I	7.0	C	2.8	P	1.9	Z	0.01
N	6.7	U	2.8	B	1.5		
S	6.3	M	2.4	V	1.0		

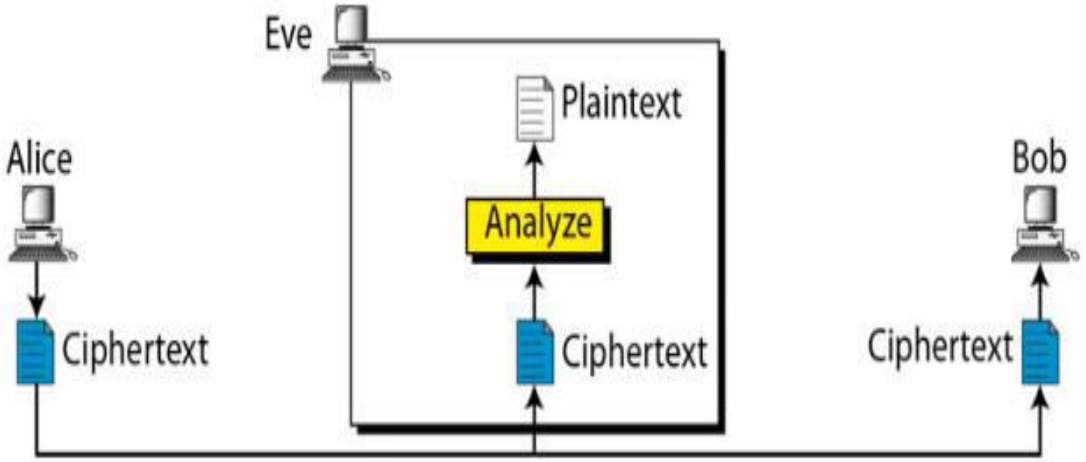
Frequency of diagrams and trigrams

Digram	TH, HE, IN, ER, AN, RE, ED, ON, ES, ST, EN, AT, TO, NT, HA, ND, OU, EA, NG, AS, OR, TI, IS, ET, IT, AR, TE, SE, HI, OF
Trigram	THE, ING, AND, HER, ERE, ENT, THA, NTH, WAS, ETH, FOR, DTH

Plaintext →	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z
Ciphertext →	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
Value →	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25

Eve has intercepted the following ciphertext. Using a statistical attack, find the plaintext.

XLILSYWIMWRSAJSVWEPIJSVJSYVQMPPMSRHSPPEVWMXMWASVX-LQSVILY-
VVCFIJSVIXLIWIPPIVVIGIMZIWQSVISJJIVW



Eve tabulate the frequency of letter in this ciphertext

I = 14 occurrences

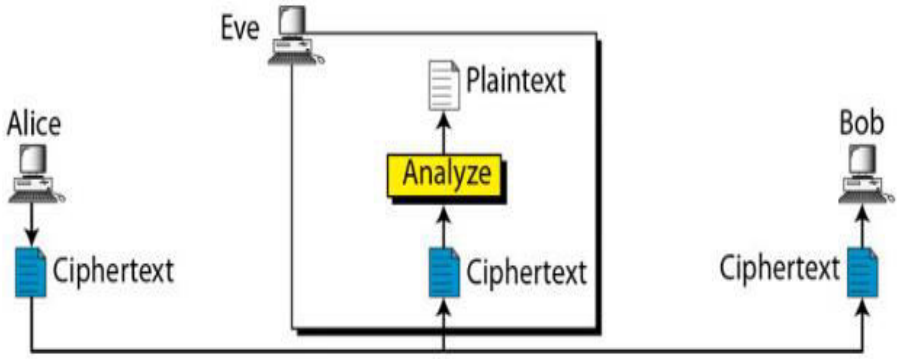
V= 13 occurrences

S =12 and so on

Plaintext →	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z
Ciphertext →	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
Value →	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25

Eve has intercepted the following ciphertext. Using a statistical attack, find the plaintext.

XLILSYWIMWRSAJSVWEPIJSVJSYVQMPPMSRHSPPEVWMXMWASVX-LQSVILY-
VVCFIJSVIXLIWIPPIVVIGIMZIWQSVISJJIVW



Letter	*Frequency*	*Letter*	*Frequency*	*Letter*	*Frequency*	*Letter*	*Frequency*
E	12.7	H	6.1	W	2.3	K	0.08
T	9.1	R	6.0	F	2.2	J	0.02
A	8.2	D	4.3	G	2.0	Q	0.01
O	7.5	L	4.0	Y	2.0	X	0.01
I	7.0	C	2.8	P	1.9	Z	0.01
N	6.7	U	2.8	B	1.5		
S	6.3	M	2.4	V	1.0		

Plaintext →	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z
Ciphertext →	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
Value →	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25

XLILSYWIMWRSAJSVWEPIJSVJSYVQMPPMSRHSPPEVWMXMWASVX-LQSVILY-
VVCFIJSVIXLIWIPPIVVIGIMZIWQSVISJJIVW

X → 23 – 4 mod 26 → 19 mod 26 = 19 → T

L → 11 – 4 mod 26 → 7 mod 26 = 7 → H

I → 8 -4 mod 26 → 4 mod 26 = 4 → E

Substitution Ciphers

Eve has intercepted the following ciphertext. Using a statistical attack, find the plaintext.

XLILSYWIMWRSAJSVWEPIJSVJSYVQMPPMSRHSPPEVWMXMWASVX-LQSVILY-
VVCFIJSVIXLIWIPPIVVIGIMZIWQSVISJJIVW

Solution

When Eve tabulates the frequency of letters in this ciphertext, she gets: I =14, V =13, S =12, and so on. The most common character is I with 14 occurrences. This means key = 4.

the house is now for sale for four million dollars it is worth more hurry before the seller receives more offers

Substitution Ciphers

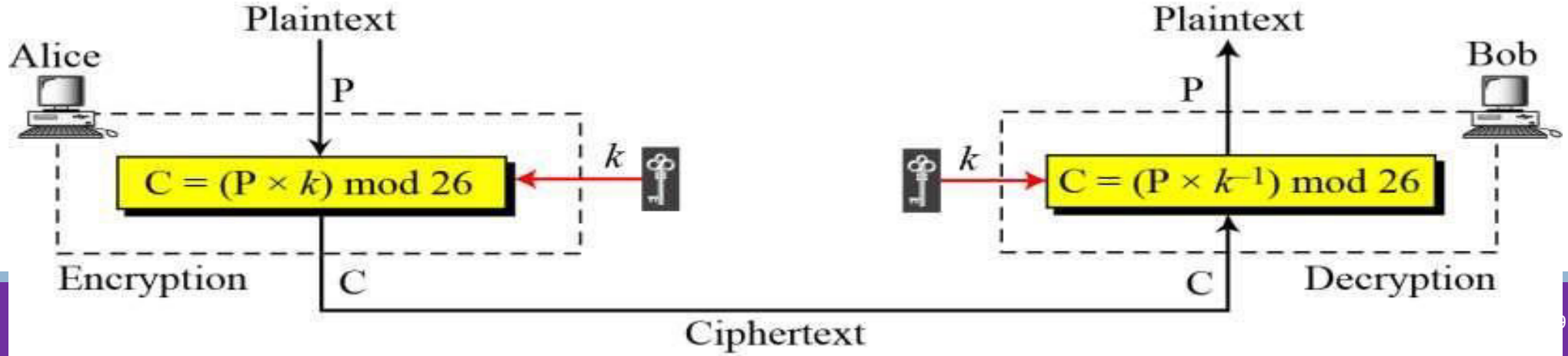
Monoalphabetic ciphers

a. Additive cipher(Shift cipher/Ceasar cipher)
b. Multiplicative ciphers
c. Affine cipher

Substitution Ciphers

Monoalphabetic ciphers - Multiplicative ciphers

- The encryption algorithm specifies multiplication of PT with key
- The decryption algorithm specifies division of CT by key
- Since operations are in Z_{26} Decryption here means multiplying PT with multiplicative inverse of key



Substitution Ciphers

In Cryptography use

Z_n when additive inverse are needed

Z_n^* when multiplicative inverse are needed

Substitution Ciphers

What is the key domain for any multiplicative inverse

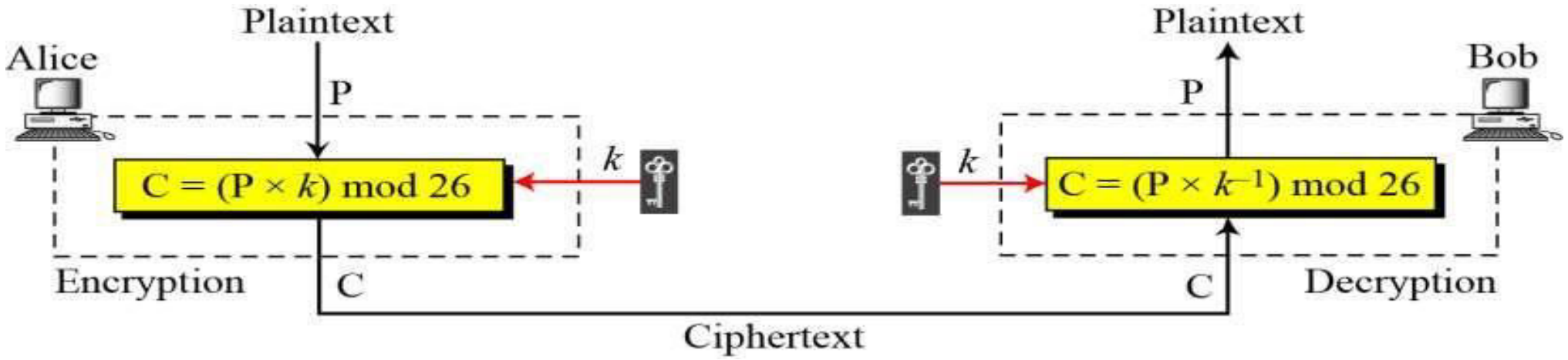
Key needs to be in Z_n^*

$Z_{26}^* = \{ 1,3,5,7,9,11,15,17,19,21,23,25\}$

Substitution Ciphers

Monoalphabetic ciphers - Multiplicative ciphers

Use multiplicative cipher to encrypt the message “hello” with a key of 7.



RAMAIAH Institute of Technology

Substitution Ciphers

Monoalphabetic ciphers - Multiplicative ciphers

Use multiplicative cipher to encrypt the message "hello" with a key of 7.

The ciphertext is "XCZZU".

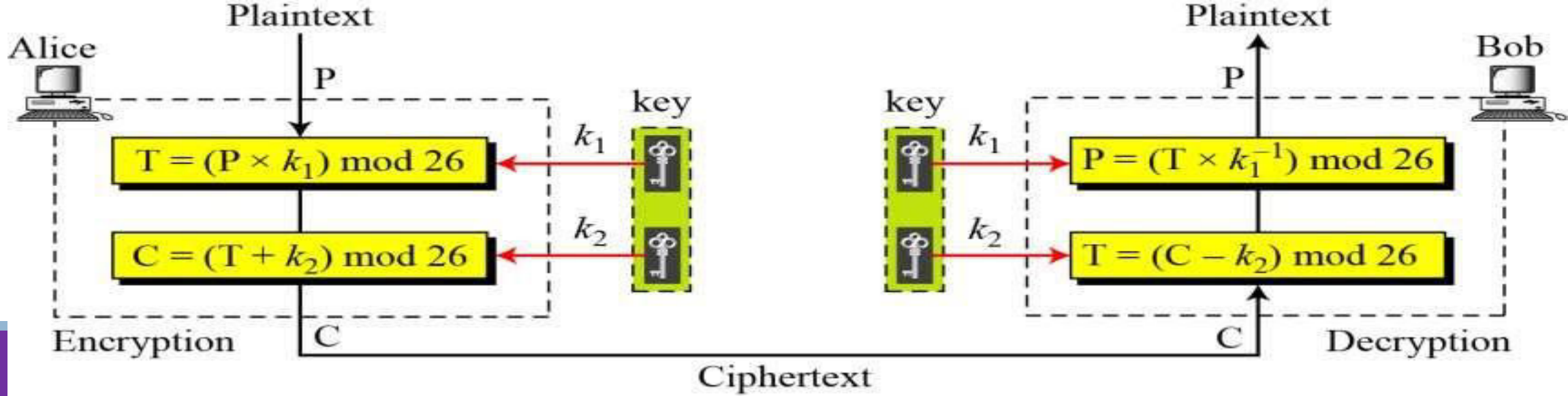
Plaintext: h $\rightarrow$ 07	Encryption: $(07 \times 07) \bmod 26$	ciphertext: 23 $\rightarrow$ X
Plaintext: e $\rightarrow$ 04	Encryption: $(04 \times 07) \bmod 26$	ciphertext: 02 $\rightarrow$ C
Plaintext: l $\rightarrow$ 11	Encryption: $(11 \times 07) \bmod 26$	ciphertext: 25 $\rightarrow$ Z
Plaintext: l $\rightarrow$ 11	Encryption: $(11 \times 07) \bmod 26$	ciphertext: 25 $\rightarrow$ Z
Plaintext: o $\rightarrow$ 14	Encryption: $(14 \times 07) \bmod 26$	ciphertext: 20 $\rightarrow$ U

RAMAIAH
Institute of Technology

Substitution Ciphers

Monoalphabetic ciphers – Affine cipher

- Combination of both cipher with a pair of keys
- First key is used with multiplicative cipher
- Second key is used with additive cipher



Substitution Ciphers

What is the key domain for any affine inverse

First key is Z_n^* and second key needs to be in Z_{26}

As we know that Z_{26}^* = { 1,3,5,7,9,11,15,17,19,21,23,25}

Size of key domain = 12 * 26 ➔ 312

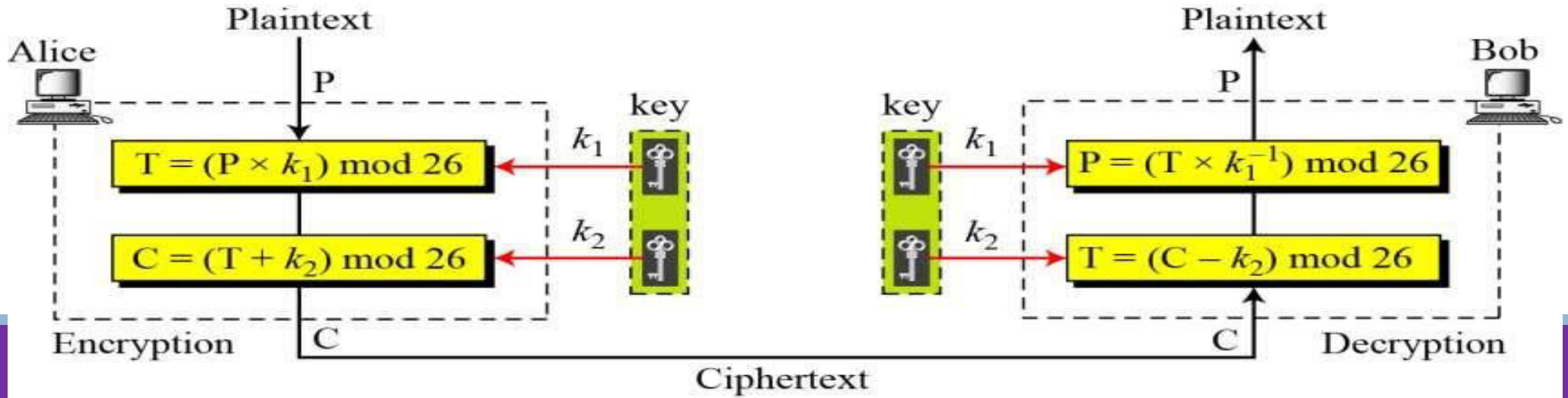
RAMAIAH
Institute of Technology

Substitution Ciphers

Use an affine cipher to encrypt the message “hello” with the key pair (7, 2).

P: h → 07
Encryption: $(07 \times 7 + 2) \bmod 26$

C: 25 → Z

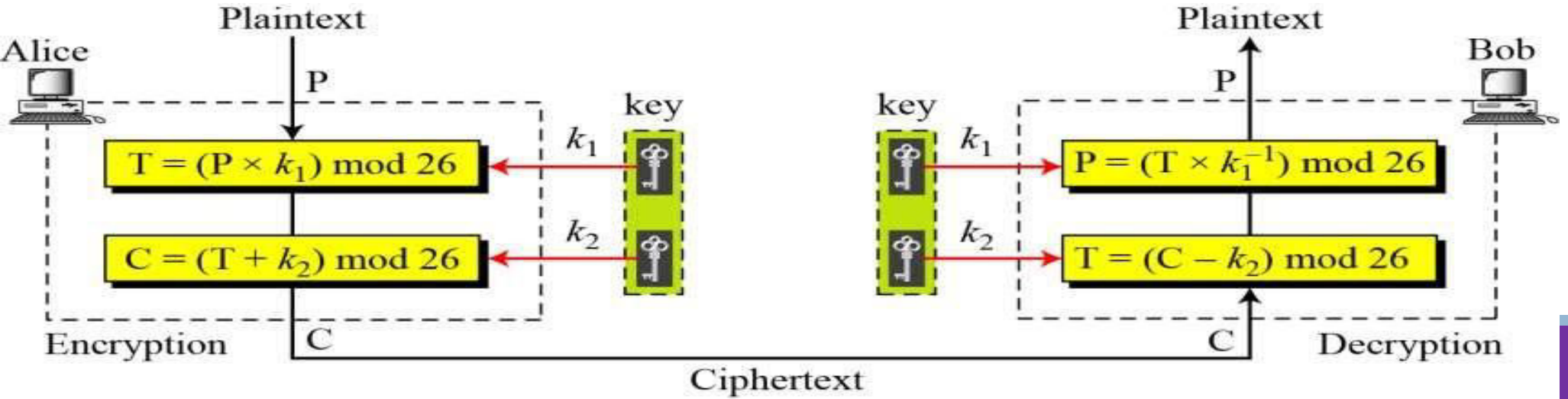


RAMAIAH Institute of Technology

Substitution Ciphers

Use an affine cipher to encrypt the message “hello” with the key pair (7, 2).

P: h → 07	Encryption: $(07 \times 7 + 2) \bmod 26$	C: 25 → Z
P: e → 04	Encryption: $(04 \times 7 + 2) \bmod 26$	C: 04 → E
P: l → 11	Encryption: $(11 \times 7 + 2) \bmod 26$	C: 01 → B
P: l → 11	Encryption: $(11 \times 7 + 2) \bmod 26$	C: 01 → B
P: o → 14	Encryption: $(14 \times 7 + 2) \bmod 26$	C: 22 → W



RAMAIAH Institute of Technology

Cipher = ZEBBW

C = Z → 25

=((25 - 2) x 7^{-1}) mod 26

= (23 x 7^{-1}) mod 26

= (23 x 15) mod 26

= 345 mod 26

= 7

= H

C = E → 04

=((4 - 2) x 7^{-1}) mod 26

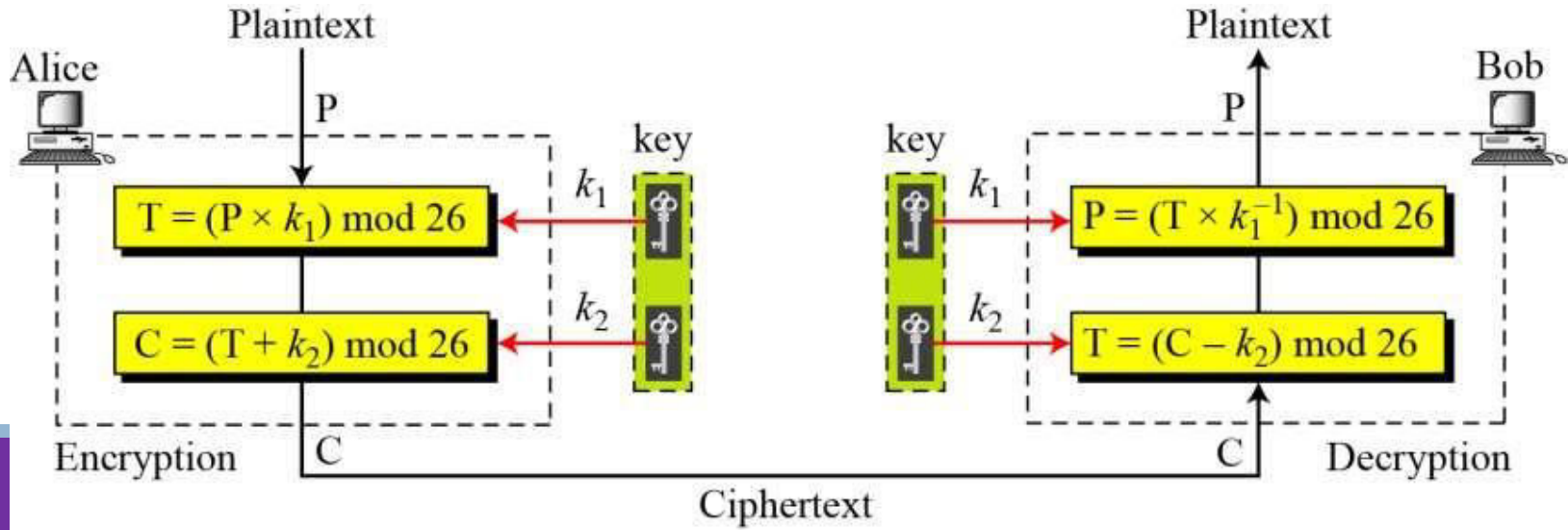
= (2 x 7^{-1}) mod 26

= (2 x 15) mod 26

= 30 mod 26

= 4

= 4

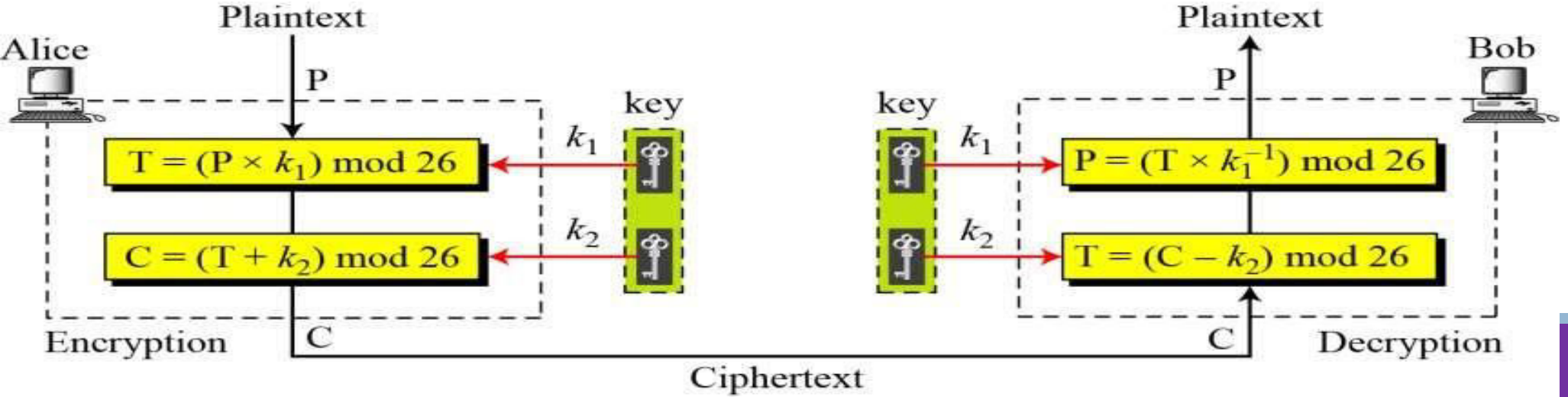


RAMAIAH
Institute of Technology

Substitution Ciphers

Use the affine cipher to decrypt the message "ZEBBW" with the key pair (7, 2) in modulus 26.

C: Z → 25	Decryption: $((25-2)\times 7^{-1}) \bmod 26$	P:07 → h
C: E → 04	Decryption: $((04-2)\times 7^{-1}) \bmod 26$	P:04 → e
C: B → 01	Decryption: $((01-2)\times 7^{-1}) \bmod 26$	P:11 → l
C: B → 01	Decryption: $((01-2)\times 7^{-1}) \bmod 26$	P:11 → l
C: W → 22	Decryption: $((22-2)\times 7^{-1}) \bmod 26$	P:14 → o



Substitution Ciphers

In general, In additive cipher

- First key k1 is used with multiplicative cipher
- Second key k2 is used with additive cipher

The additive cipher is a special case of an affine cipher in which $k_1 = 1$.

The multiplicative cipher is a special case of affine cipher in which $k_2 = 0$.

Substitution Ciphers

Because additive, multiplicative, and affine ciphers have small key domains, they are very vulnerable to brute-force attack.

A better solution is to create a mapping between each plaintext character and the corresponding ciphertext character.

Alice and Bob can agree on a table showing the mapping for each character.

An example key for monoalphabetic substitution cipher

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

RAMAIAH Institute of Technology

Substitution Ciphers

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

We can use the key to encrypt the message

this message is easy to encrypt but hard to find the key

The ciphertext is

RAMAIAH Institute of Technology

Substitution Ciphers

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

We can use the key to encrypt the message

this message is easy to encrypt but hard to find the key

The ciphertext is

ICFVQRVVNEFVRNVSIYRGAHSLIOJICNHTIYBFGTICRXRS

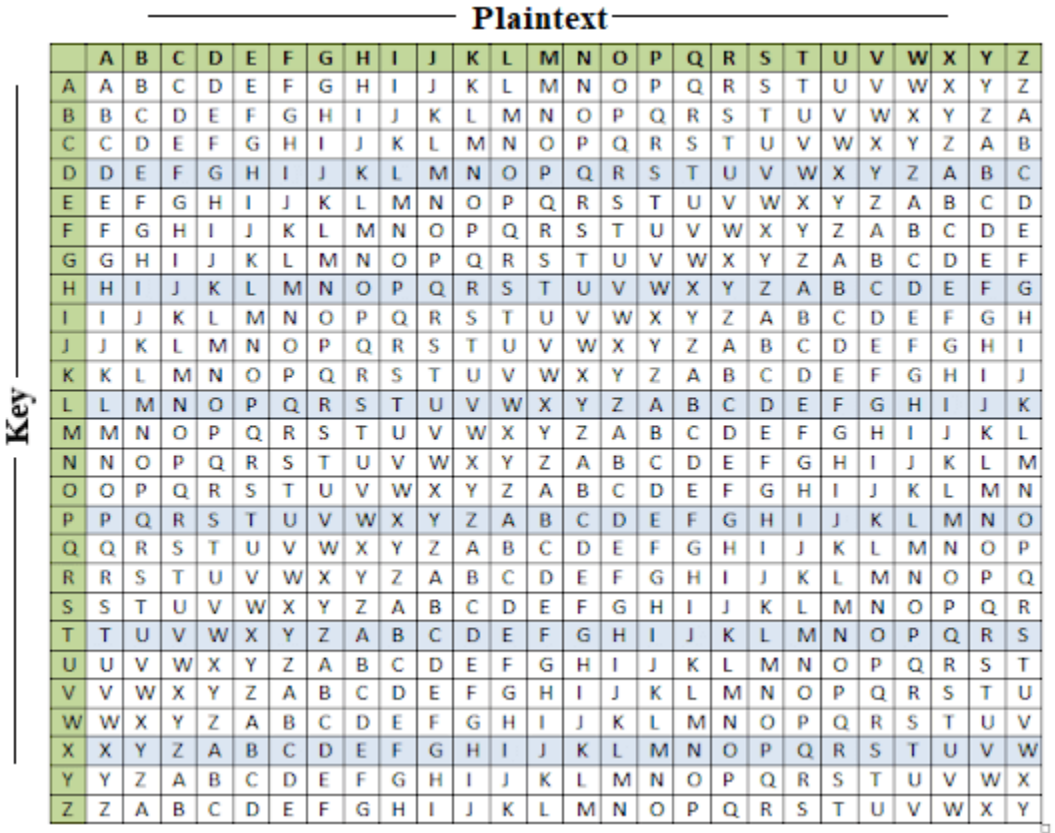
RAMAIAH
Institute of Technology

Polyalphabetic Ciphers

- In polyalphabetic substitution, each occurrence of a character may have a different substitute.
- The relationship between a character in the plaintext to a character in the ciphertext is one-to-many.

PT = WELCOME

CT = XGPHUTR



Key \ Plaintext	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

Substitution Ciphers

Polyalphabetic ciphers

a. Autokey cipher
b. Playfair cipher
c. Vigener cipher
d. Hill cipher
e. One time pad
f. Rotor cipher

RAMAIAH
Institute of Technology

Polyalphabetic Ciphers

Autokey cipher

- In this cipher, key is a stream of subkeys, in which each subkey is used to encrypt the corresponding character in the plaintext.

- The first subkey is predetermined secret value agreed between Sender and receiver

$$P = P_1P_2P_3 \ldots \qquad C = C_1C_2C_3 \ldots \qquad k = (k_1, P_1, P_2, \ldots)$$

Encryption: $C_i = (P_i + k_i) \bmod 26$ Decryption: $P_i = (C_i - k_i) \bmod 26$

Plaintext →	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z
Ciphertext →	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
Value →	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25

Assume that Alice and Bob agreed to use an autokey cipher with initial key value k1 = 12.

Now Alice wants to send Bob the message "Attack is today". Enciphering is done character by character.

Plaintext:	a	t	t	a	c	k	i	s	t	o	d	a	y
P's Values:	00	19	19	00	02	10	08	18	19	14	03	00	24
Key stream:	*12*	*00*	*19*										
C's Values:	12	19	12										
Ciphertext:	**M**	**T**	**M**										

Plaintext →	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z
Ciphertext →	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
Value →	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25

Assume that Alice and Bob agreed to use an autokey cipher with initial key value k1 = 12.

Now Alice wants to send Bob the message "Attack is today". Enciphering is done character by character.

Plaintext:	a	t	t	a	c	k	i	s	t	o	d	a	y
P's Values:	00	19	19	00	02	10	08	18	19	14	03	00	24
Key stream:	*12*	*00*	*19*	*19*	*00*	*02*	*10*	*08*	*18*	*19*	*14*	*03*	*00*
C's Values:	12	19	12	19	02	12	18	00	11	7	17	03	24
Ciphertext:	**M**	**T**	**M**	**T**	**C**	**M**	**S**	**A**	**L**	**H**	**R**	**D**	**Y**

RAMAIAH
Institute of Technology

Polyalphabetic Ciphers

Playfair cipher

- The best-known digraph substitution cipher, invented in 1854 by Charles Wheatstone but was named after Lord Playfair who promoted the use of the cipher.
- Used by British army during World war I.
- Secret key is made up of 25 characters arranged in 5*5 matrix (I and J are considered same)

Secret Key =

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

RAMAIAH
Institute of Technology

Polyalphabetic Ciphers

The Playfair Cipher Encryption Algorithm:

1.Generate the key Square(5×5):

The key square is a 5×5 grid of alphabets that acts as the key for encrypting the plaintext.

The initial alphabets in the key square are the unique alphabets of the key in the order in which they appear followed by the remaining letters of the alphabet in order.

Secret Key =

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

keyword = **ATHENS**

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

Polyalphabetic Ciphers

The Playfair Cipher Encryption Algorithm:

Before encryption:

- Divide the plaint text into digraphs
- If two letters in a pair are the same, a bogus letter is inserted to separate them
- After inserting bogus letter, if number of character is odd, one extra bogus character is added at the end to make number of characters even

RAMAIAH
Institute of Technology

Polyalphabetic Ciphers

PT = attack

Digrams → at ta ck

PT = balloon

Digrams → ba ll oo n → ba lx lo on

PT = msit academy

Digrams → ms it ac ad em yx

RAMAIAH Institute of Technology

Polyalphabetic Ciphers

The Playfair Cipher Encryption Algorithm:

2.Encrypt the Plaintext → Three cipher rules

a) If the two letters in a pair are located in the same row of the secret key, the corresponding encrypted character for each character is the next letter to the right in the same row(wrap to beginning of row)

b) If the two letters in a pair are located in the same column of the secret key, the corresponding encrypted character for each character is the letter beneath in the same column(wrap to beginning of column)

c) If the two letter in a pair are not in the same row or column of the secret, the corresponding encrypted character for each letter is a letter that is in its own row but in the same column as the other letter. (Form a rectangle)

Polyalphabetic Ciphers

Encrypt the plaintext “hello” using the key shown

PT = hello

Digraphs = he ll o

he lx lo

EC QZ BX

Secret Key =

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

he → EC lx → QZ lo → BX

Plaintext: hello Ciphertext: ECQZBX

RAMAIAH
Institute of Technology

Polyalphabetic Ciphers

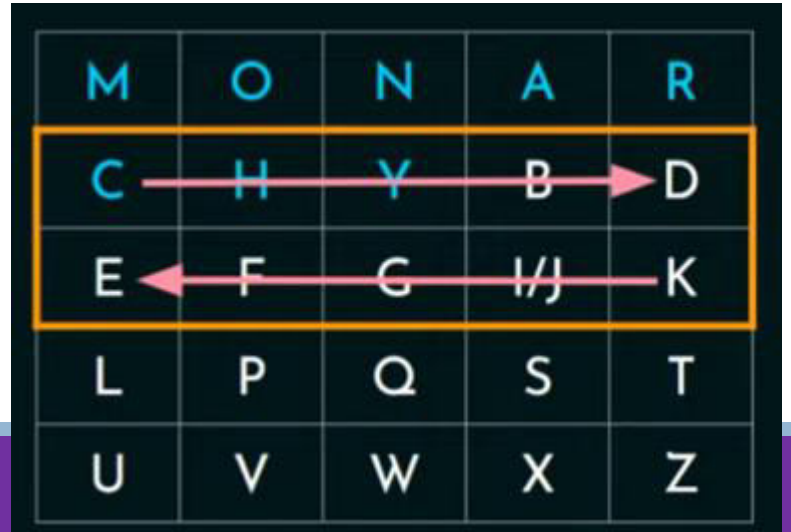
Example 1: attack

Digrams: at ta ck

at	ta	ck
RS	SR	DE

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

1. Digrams.
2. Repeating Letters - Filler letter.
3. Same Column | ↓ | Wrap around
4. Same row | → | Wrap around.
5. Rectangle | ⇆ | Swap



RAMAIAH
Institute of Technology

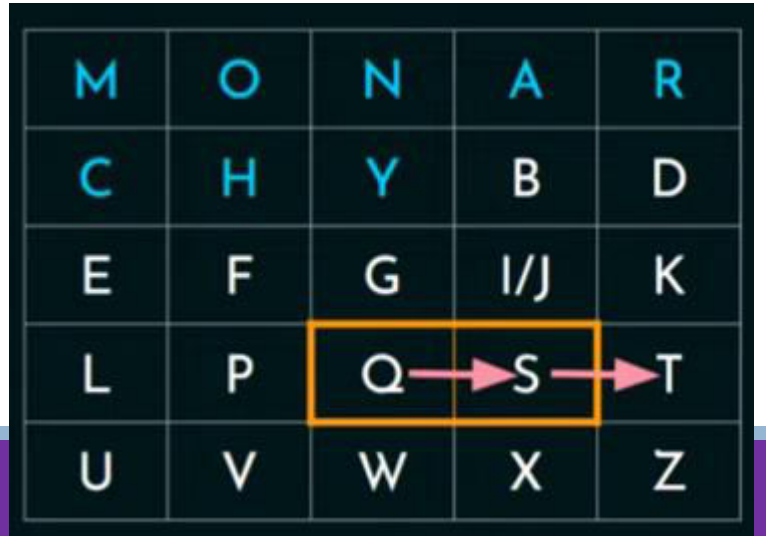
Polyalphabetic Ciphers

Example 2: mosque

mo	sq	ue
ON	TS	ML

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

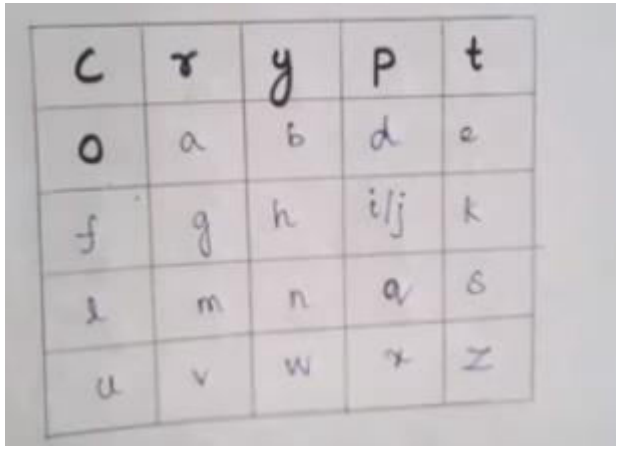
1. Digrams.
2. Repeating Letters - Filler letter.
3. Same Column | ↓ | Wrap around
4. Same row | → | Wrap around.
5. Rectangle | ⇆ | Swap



Polyalphabetic Ciphers

Encrypt the plaintext "**PLEASE SAVE ME** " using the key = CRYPTO

Digraphs = PL EA SE SA VE ME
CIPHER = CQ OB ZK ME ZA SA

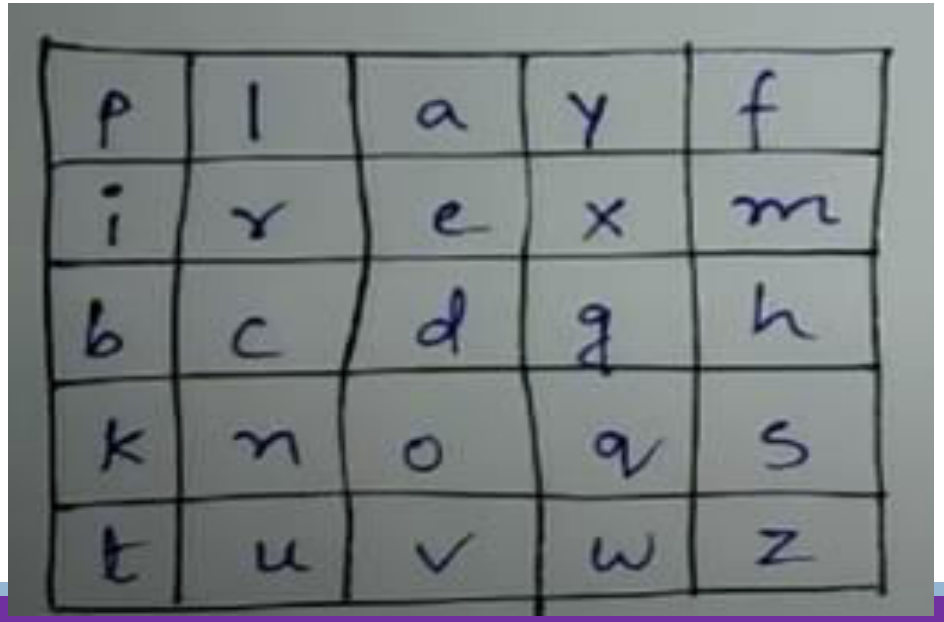


CIPHER = CQ OB ZK ME ZA SA
Digraphs = PL EA SE SA VE ME

1. Digrams.
2. Repeating Letters - Filler letter.
3. Same Column | ↓ | Wrap around.
4. Same row | → | Wrap around.
5. Rectangle | ⇆ | Swap

Polyalphabetic Ciphers

Encrypt the
plaintext "**HIDE THE GOAL IN THE TREE STUMP**" using the key = PLAYFAIR EXAMPLE



Vigenere Cipher

- Designed by Blaise de Vigenere, mathematician
- Vigenere cipher uses a different strategy to create the key stream .
- Keystream is a repetition of an initial secret key stream of length m, where 1 ≤ m ≤ 26.
- Suppose Alice and Bob agree k= (k1,k2,k3…….km)

$$P = P_1P_2P_3 \ldots \qquad C = C_1C_2C_3 \ldots \qquad K = [(k_1, k_2, \ldots, k_m), (k_1, k_2, \ldots, k_m), \ldots]$$

$$\text{Encryption: } C_i = P_i + k_i \qquad \text{Decryption: } P_i = C_i - k_i$$

Encrypt the message “She is listening” using the 6-character keyword “PASCAL”.

Plaintext →	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z
Ciphertext →	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
Value →	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25

"She is listening" using the 6-character keyword "PASCAL".

The initial key stream is (15, 0, 18, 2, 0, 11). The key stream is the repetition of this initial key stream (as many times as needed).

Plaintext:	s	h	e	i	s	l	i	s	t	e	n	i	n	g
P's values:	18	07	04	08	18	11	08	18	19	04	13	08	13	06
Key stream:	***15***	***00***	***18***	***02***	***00***	***11***								
C's values:	**07**	**07**	**22**	**10**	**18**	**22**								
Ciphertext:	**H**	**H**	**W**	**K**	**S**	**W**								

Plaintext →	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z
Ciphertext →	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
Value →	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25

"She is listening" using the 6-character keyword "PASCAL".

The initial key stream is (15, 0, 18, 2, 0, 11). The key stream is the repetition of this initial key stream (as many times as needed).

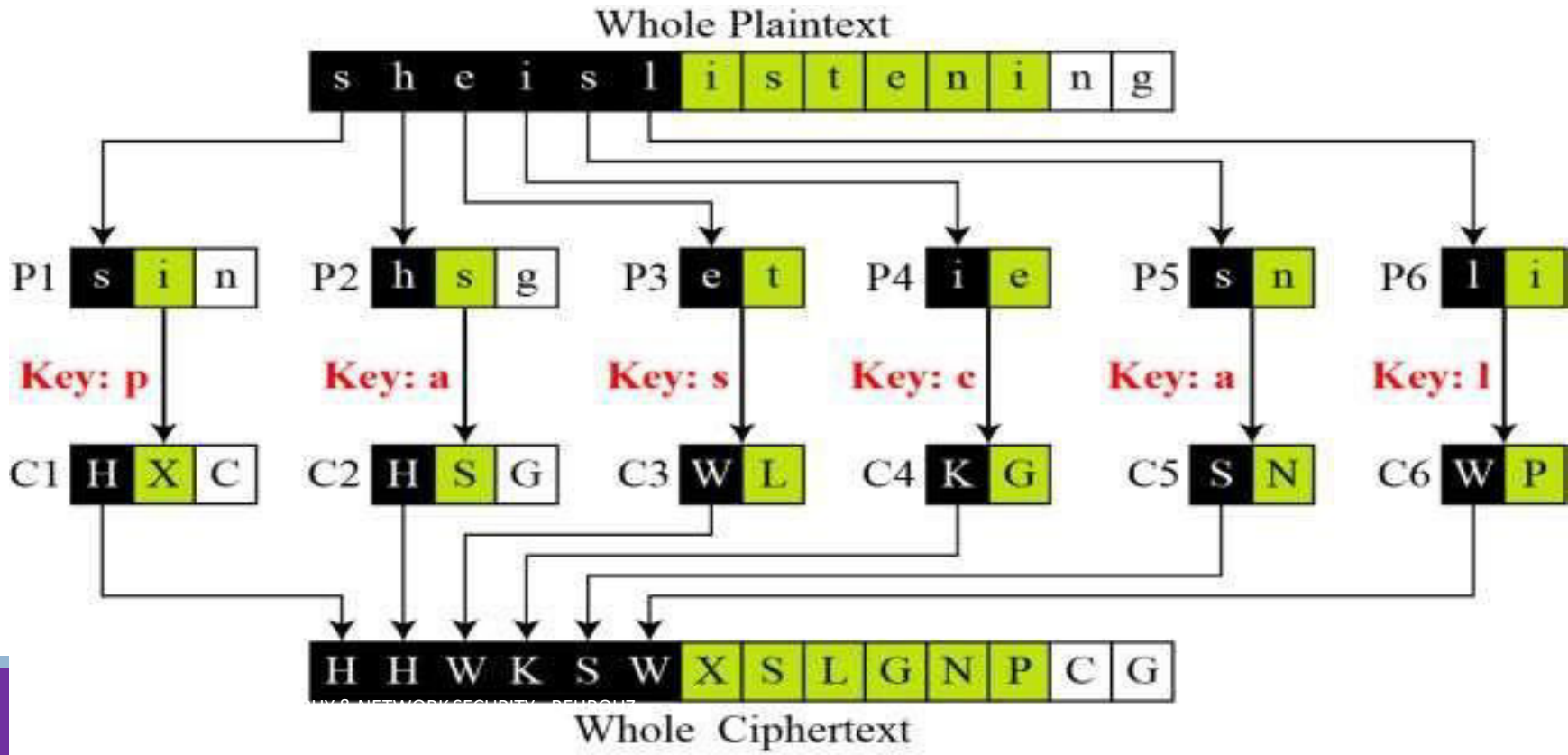
Plaintext:	s	h	e	i	s	l	i	s	t	e	n	i	n	g
P's values:	18	07	04	08	18	11	08	18	19	04	13	08	13	06
Key stream:	***15***	***00***	***18***	***02***	***00***	***11***	***15***	***00***	***18***	***02***	***00***	***11***	***15***	***00***
C's values:	**07**	**07**	**22**	**10**	**18**	**22**	**23**	**18**	**11**	**6**	**13**	**19**	**02**	**06**
Ciphertext:	**H**	**H**	**W**	**K**	**S**	**W**	**X**	**S**	**L**	**G**	**N**	**T**	**C**	**G**

Vigenere cipher can be seen as combinations of m additive ciphers.

PT "She is listening"

Keyword "PASCAL".

A Vigenere cipher as a combination of m additive ciphers



RAMAIAH
Institute of Technology

We can say that the additive cipher is a special case of Vigenere cipher in which m = 1.

A Vigenere Tableau

	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	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

Plain text

"She is listening"

keyword

"PASCAL".

s	h	e	i	s	l	i	s	t	e	n	i	n	g
18	07	04	08	18	11	08	18	19	04	13	08	13	06
15	*00*	*18*	*02*	*00*	*11*	*15*	*00*	*18*	*02*	*00*	*11*	*15*	*00*
07	**07**	**22**	**10**	**18**	**22**	**23**	**18**	**11**	**6**	**13**	**19**	**02**	**06**
H	**H**	**W**	**K**	**S**	**W**	**X**	**S**	**L**	**G**	**N**	**T**	**C**	**G**

Cryptanalysis of Vigenere Ciphers

Eve can use technique to decipher the intercepted cipher text.

The cryptanalysis consist of :

- Finding the length of key
- Finding the key

Cryptanalysis of Vigenere Ciphers

Several methods to find the length of key

- Kasiski test

RAMAIAH
Institute of Technology

Vigenere Cipher (Crypanalysis)

The Kasiski test for repetition of three-character segments

Let us assume eve intercepted the following ciphertext:

LIOMWGFEGGDVWGHHCQUCRHRWAGWIOWQLKGZETKKMEVLWPCZVGTH-
VTSGXQOVGCSVETQLTJSUMVWVEUVLXEWSLGFZMVVWLGYHCUSWXQH-
KVGSHEEVFLCFDGVSUMPHKIRZDMPHHBVWVWJWIXGFWLTSHGJOUEEHH-
VUCFVGOWICQLTJSUXGLW

LIOMWGFEGGDVWGHHCQUCRHRWAGWIOWQLKGZETKKMEVLWPCZVGTH-
VTSGXQOVGCSVETQLTJSUMVWVEUVLXEWSLGFZMVVWLGYHCUSWXQH-
KVGSHEEVFLCFDGVSUMPHKIRZDMPHHBVWVWJWIXGFWLTSHGJOUEEHH-
VUCFVGOWICQLTJSUXGLW

RAMAIAH
Institute of Technology

Vigenere Cipher (Crypanalysis)

The Kasiski test for repetition of three-character segments yields the results shown in Table

LIOMWGFEGGDVWGHHCQUCRHRWAGWIOWQLKGZETKKMEVLWPCZVGTH-
VTSGXQOVGCSVETQLTJSUMVWVEUVLXEWSLGFZMVVWLGYHCUSWXQH-
KVGSHEEVFLCFDGVSUMPHKIRZDMPHHBVWVWJWIXGFWLTSHGJOUEEHH-
VUCFVGOWICQLTJSUXGLW

String	*First Index*	*Second Index*	*Difference*
JSU	68	168	100
SUM	69	117	48
VWV	72	132	60
MPH	119	127	8

One Time pad

- One of the goals of cryptography is perfect secrecy.
- A study by Shannon has shown that perfect secrecy can be achieved if each plaintext symbol is encrypted with a key randomly chosen from a key domain.
- This idea is used in a cipher called one-time pad, invented by Vernam.

One Time pad

- It is a method of encrypting alphabetic plain text.
- It is one of the Substitution techniques which converts plain text into ciphertext.
- In this mechanism, we assign a number to each character of the Plain-Text.

Plaintext →	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z
Ciphertext →	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
Value →	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25

One Time pad

- The key must be the same size as the message being sent.
- The key must be truly random.
- Keys must be securely shared between the sending and receiving parties.

Because of these strict conditions, the use of one-time pad over digital media is impracticable

RAMAIAH
Institute of Technology

One Time pad

- The relation between the key and plain text: In this algorithm, the length of the key should be equal to that of plain text.

- Encrypt the Plaintext = HELLO and Key = MONEY

- HELLO → 7 4 11 11 14
- MONEY→ 12 14 13 4 24

---

19 18 24 15 (38 – 26)

19 18 24 15 12 → **T S Y P M**

Plaintext →	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z
Ciphertext →	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
Value →	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25

RAMAIAH
Institute of Technology

One Time pad

CT= TSYPM → 19 18 24 15 12

KEY=MONEY → 12 14 3 4 24

---

7 4 11 11 -12 + 26

7 4 11 11 14

H E L L O

Plaintext →	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z
Ciphertext →	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
Value →	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25

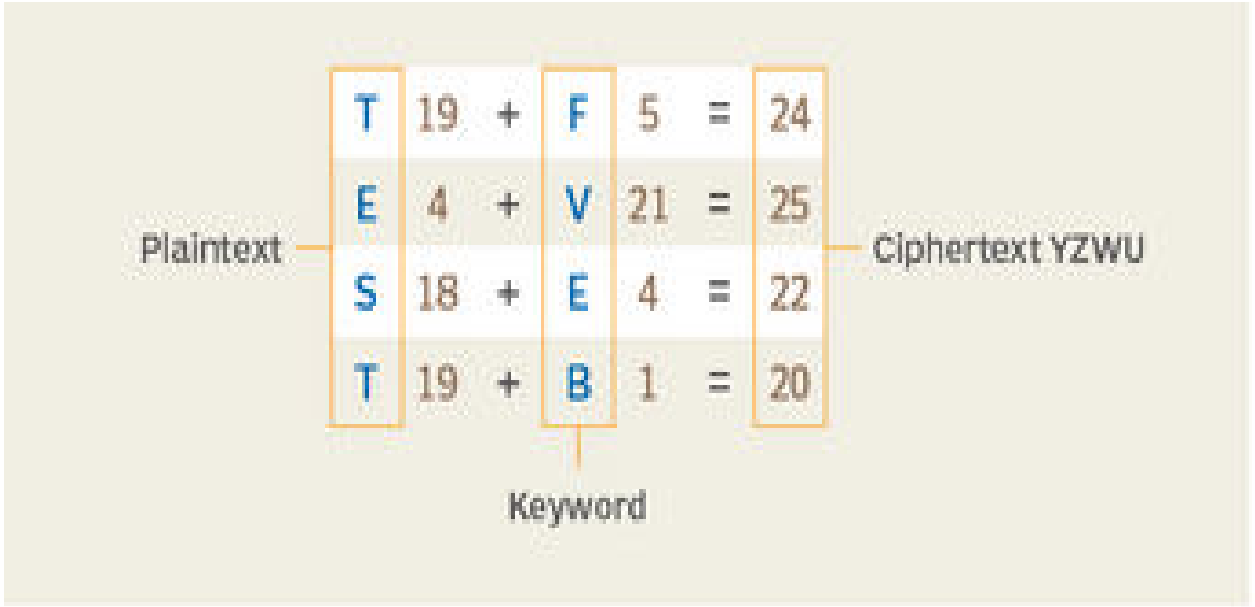
One Time pad

Plaintext = TEST

Key = FVEB

PT = ENIGMA

Key = KEYWOR



One Time pad

When a message is to be sent, the sender uses the secret key to encrypt each character one at a time.

If a computer is used, each bit in the character, which is usually eight bits in length is exclusively OR'ed with the corresponding bit in the secret key.

With a one-time pad, the encryption algorithm is simply the XOR operation.

One Time pad

A	B	A **XOR** B
0	0	0
0	1	1
1	0	1
1	1	0

ENCRYPT

```
  00110101  Plaintext
⊕ 11100011  Secret Key
----------
= 11010110  Ciphertext
```

DECRYPT

```
  11010110  Ciphertext
⊕ 11100011  Secret Key
----------
= 00110101  Plaintext
```

Hill Cipher

- The Hill Cipher was invented by Lester S. Hill in 1929
- It acts on groups of letters.
- It is a polygraphic substitution cipher, as it can work on digraphs, trigraphs (3 letter blocks) or theoretically any sized blocks.

Hill Cipher

- Key is a square matrix of size m x m matrix in which m is the size of the block(2 x 2 matrix for digraphs, a 3 x 3 matrix for trigraphs).

$$\mathrm{K} = \begin{bmatrix} k_{11} & k_{12} & \cdots & k_{1m} \\ k_{21} & k_{22} & \cdots & k_{2m} \\ \vdots & \vdots & & \vdots \\ k_{\mathrm{m1}} & k_{\mathrm{m2}} & \cdots & k_{mm} \end{bmatrix}$$

Hill Cipher

- **Encryption**

  Turn the plaintext into digraphs (or trigraphs) and each of these into a column vector.

  To encrypt a message, each block of n letters is multiplied by an m × m matrix, against modulus 26. C = K*P mod 26

- **Decryption**

  To decrypt the message, each block is multiplied by the inverse of the matrix

Hill Cipher

Encrypt the plaintext message "short example" using the keyword hill with a 2 x 2 matrix.

Hill Cipher

- The first step is to turn the keyword hill into a matrix.
- hill → 7 8 11 11

$$\begin{pmatrix} H & I \\ L & L \end{pmatrix} \rightarrow \begin{pmatrix} 7 & 8 \\ 11 & 11 \end{pmatrix}$$

Plaintext →	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z
Ciphertext →	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
Value →	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25

RAMAIAH
Institute of Technology

Hill Cipher

Split the plaintext into digraphs, and write these as column vectors.

short example → sh or te xa mp l e

18 7 14 17 19 4 23 0 12 15 11 4

$$\begin{pmatrix} s \\ h \end{pmatrix} \begin{pmatrix} o \\ r \end{pmatrix} \begin{pmatrix} t \\ e \end{pmatrix} \begin{pmatrix} x \\ a \end{pmatrix} \begin{pmatrix} m \\ p \end{pmatrix} \begin{pmatrix} l \\ e \end{pmatrix}$$

$$\begin{pmatrix} 18 \\ 7 \end{pmatrix} \begin{pmatrix} 14 \\ 17 \end{pmatrix} \begin{pmatrix} 19 \\ 4 \end{pmatrix} \begin{pmatrix} 23 \\ 0 \end{pmatrix} \begin{pmatrix} 12 \\ 15 \end{pmatrix} \begin{pmatrix} 11 \\ 4 \end{pmatrix}$$

Plaintext →	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z
Ciphertext →	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
Value →	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25

Plaintext →	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z
Ciphertext →	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
Value →	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25

Hill Cipher

Encryption : Perform matrix multiplication, multiply the key matrix by each column vector in turn.

$$\begin{pmatrix}18\\7\end{pmatrix}\begin{pmatrix}14\\17\end{pmatrix}\begin{pmatrix}19\\4\end{pmatrix}\begin{pmatrix}23\\0\end{pmatrix}\begin{pmatrix}12\\15\end{pmatrix}\begin{pmatrix}11\\4\end{pmatrix} \qquad \text{Key} = \begin{pmatrix}7 & 8\\11 & 11\end{pmatrix}$$

C = K*P mod 26

$$= \begin{pmatrix}7 & 8\\11 & 11\end{pmatrix}\begin{pmatrix}18\\7\end{pmatrix} \bmod 26$$

$$= \quad 7\times 18 + 8\times 7 = 182$$

$$11\times 18 + 11\times 7 = 275$$

$$\begin{pmatrix}7 & 8\\11 & 11\end{pmatrix}\begin{pmatrix}18\\7\end{pmatrix} = \begin{pmatrix}182\\275\end{pmatrix}$$

$$= \begin{pmatrix}182\\275\end{pmatrix} \bmod 26$$

$$= \begin{pmatrix}0\\15\end{pmatrix} \quad = \begin{pmatrix}A\\P\end{pmatrix}$$

Hill Cipher

Plaintext →	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z
Ciphertext →	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
Value →	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25

C = K*P mod 26

$$\begin{pmatrix} 7 & 8 \\ 11 & 11 \end{pmatrix} \begin{pmatrix} 14 \\ 17 \end{pmatrix} mod\ 26$$

$$7 \times 14 + 8 \times 17 = 234$$

$$11 \times 14 + 11 \times 17 = 341$$

$$= \begin{pmatrix} 234 \\ 341 \end{pmatrix} mod\ 26$$

$$= \begin{pmatrix} 0 \\ 3 \end{pmatrix} = \begin{pmatrix} A \\ D \end{pmatrix}$$

$$\begin{pmatrix} 18 \\ 7 \end{pmatrix} \begin{pmatrix} 14 \\ 17 \end{pmatrix} \begin{pmatrix} 19 \\ 4 \end{pmatrix} \begin{pmatrix} 23 \\ 0 \end{pmatrix} \begin{pmatrix} 12 \\ 15 \end{pmatrix} \begin{pmatrix} 11 \\ 4 \end{pmatrix}$$

Hill Cipher

Plaintext →	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z
Ciphertext →	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
Value →	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25

C = K*P mod 26

$$\begin{pmatrix}7 & 8\\11 & 11\end{pmatrix}\begin{pmatrix}19\\4\end{pmatrix} \ mod\ 26$$

$$7 \times 19 + 8 \times 4 = 165$$

$$11 \times 19 + 11 \times 4 = 253$$

$$= \begin{pmatrix}165\\253\end{pmatrix} mod\ 26$$

$$= \begin{pmatrix}9\\19\end{pmatrix} = \begin{pmatrix}J\\T\end{pmatrix}$$

$$\begin{pmatrix}18\\7\end{pmatrix}\begin{pmatrix}14\\17\end{pmatrix}\begin{pmatrix}19\\4\end{pmatrix}\begin{pmatrix}23\\0\end{pmatrix}\begin{pmatrix}12\\15\end{pmatrix}\begin{pmatrix}11\\4\end{pmatrix}$$

Hill Cipher

Plaintext →	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z
Ciphertext →	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
Value →	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25

C = K*P mod 26

$$\begin{pmatrix} 7 & 8 \\ 11 & 11 \end{pmatrix}\begin{pmatrix} 23 \\ 0 \end{pmatrix} = \begin{pmatrix} 161 \\ 253 \end{pmatrix} \ mod\ 26$$

$$\begin{pmatrix} 5 \\ 19 \end{pmatrix} = \begin{pmatrix} F \\ T \end{pmatrix}$$

$$\begin{pmatrix} 18 \\ 7 \end{pmatrix}\begin{pmatrix} 14 \\ 17 \end{pmatrix}\begin{pmatrix} 19 \\ 4 \end{pmatrix}\begin{pmatrix} 23 \\ 0 \end{pmatrix}\begin{pmatrix} 12 \\ 15 \end{pmatrix}\begin{pmatrix} 11 \\ 4 \end{pmatrix}$$

Hill Cipher

Plaintext →	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z
Ciphertext →	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
Value →	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25

C = K*P mod 26

$$\begin{pmatrix}7 & 8\\ 11 & 11\end{pmatrix}\begin{pmatrix}12\\ 15\end{pmatrix} = \begin{pmatrix}204\\ 297\end{pmatrix} mod\ 26$$

$$= \begin{pmatrix}22\\ 11\end{pmatrix} = \begin{pmatrix}W\\ L\end{pmatrix}$$

$$\begin{pmatrix}18\\ 7\end{pmatrix}\begin{pmatrix}14\\ 17\end{pmatrix}\begin{pmatrix}19\\ 4\end{pmatrix}\begin{pmatrix}23\\ 0\end{pmatrix}\begin{pmatrix}12\\ 15\end{pmatrix}\begin{pmatrix}11\\ 4\end{pmatrix}$$

Hill Cipher

Plaintext →	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z
Ciphertext →	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
Value →	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25

C = K*P mod 26

$$\begin{pmatrix}18\\7\end{pmatrix}\begin{pmatrix}14\\17\end{pmatrix}\begin{pmatrix}19\\4\end{pmatrix}\begin{pmatrix}23\\0\end{pmatrix}\begin{pmatrix}12\\15\end{pmatrix}\begin{pmatrix}11\\4\end{pmatrix}$$

$$\begin{pmatrix}7 & 8\\11 & 11\end{pmatrix}\begin{pmatrix}11\\4\end{pmatrix} = \begin{pmatrix}109\\165\end{pmatrix} mod\ 26 = \begin{pmatrix}5\\9\end{pmatrix} = \begin{pmatrix}F\\J\end{pmatrix}$$

Cipher text = APADJTFTWLFJ

Hill Cipher

Plaintext →	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z
Ciphertext →	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
Value →	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25

Decryption : Perform inverse matrix multiplication

Cipher text = APADJTFTWLFJ

Key = $\begin{pmatrix} 7 & 8 \\ 11 & 11 \end{pmatrix} \begin{bmatrix} a & b \\ c & d \end{bmatrix}$

$P = K^{-1} * C \bmod 26$

Find out inverse matrix of given key matrix.

$$K^{-1} = \frac{1}{|K|} * K_{adj}$$

RAMAIAH Institute of Technology

Hill Cipher

Plaintext →	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z
Ciphertext →	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
Value →	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25

Cipher text = APADJTFTWLFJ

$$K = \begin{pmatrix} 7 & 8 \\ 11 & 11 \end{pmatrix} \begin{bmatrix} a & b \\ c & d \end{bmatrix}$$

Find out inverse matrix of given key matrix.

$$K^{-1} = \frac{1}{|K|} * K_{adj}$$

$|K| = ad - bc = 7*11 - 8*11 = 77 - 88 \rightarrow -11 \bmod 26 = 15$

$$K_{adj} = \begin{bmatrix} d & -b \\ -c & a \end{bmatrix} \begin{pmatrix} 11 & -8 \\ -11 & 7 \end{pmatrix}$$

Hill Cipher

Plaintext →	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z
Ciphertext →	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
Value →	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25

Cipher text = APADJTFTWLFJ

$$K = \begin{pmatrix} 7 & 8 \\ 11 & 11 \end{pmatrix} \begin{bmatrix} a & b \\ c & d \end{bmatrix}$$

Find out inverse matrix of given key matrix.

$$K^{-1} = \frac{1}{|K|} * K_{adj}$$

$$= \frac{1}{15} * \begin{pmatrix} 11 & -8 \\ -11 & 7 \end{pmatrix}$$

$$= 15^{-1} * \begin{pmatrix} 11 & -8 \\ -11 & 7 \end{pmatrix} \text{ mod } 26$$

$15^{-1} \bmod 26 = ?$

$15 (?) \bmod 26 = 1$

$15(1) \bmod 26 = 15$ not equal to 1

$15(2) \bmod 26 = 4$ not equal to 1

.

.

.

$15(7) \bmod 26 = 1$

So, $15^{-1} \bmod 26 = 7$

Find the multiplicative inverse of 15 in Z_{26}.

q	r1	r2	r	t1	t2	t
1	26	15	11	0	1	-1
1	15	11	4	1	-1	2
2	11	4	3	-1	2	-5
1	4	3	1	2	-5	7
3	3	1	0	-5	7	-26
	1	0		7	-26	

$r_1 \leftarrow n; \quad r_2 \leftarrow b;$
$t_1 \leftarrow 0; \quad t_2 \leftarrow 1;$

while $(r_2 > 0)$
{
$q \leftarrow r_1 / r_2;$

$r \leftarrow r_1 - q \times r_2;$
$r_1 \leftarrow r_2; \quad r_2 \leftarrow r;$

$t \leftarrow t_1 - q \times t_2;$
$t_1 \leftarrow t_2; \quad t_2 \leftarrow t;$

}
if $(r_1 = 1)$ then $b^{-1} \leftarrow t_1$

The gcd (26, 15) is 1; the inverse of 15 is 7

Hill Cipher

Find out inverse matrix of given key matrix.

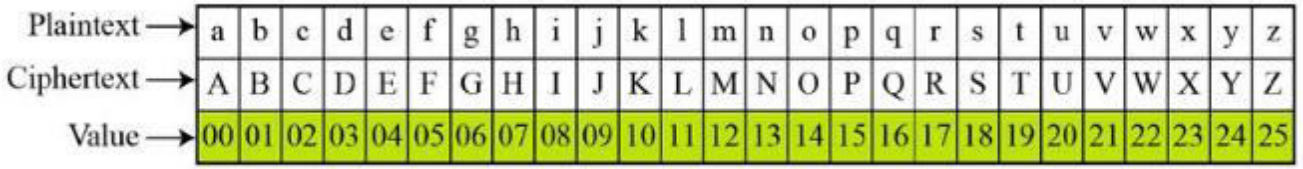
$$K^{-1} = \frac{1}{|K|} * K_{adj}$$

$$= 7 * \begin{pmatrix} 11 & -8 \\ -11 & 7 \end{pmatrix} \text{ mod } 26$$

$$= 7 * \begin{pmatrix} 11 & 18 \\ 15 & 7 \end{pmatrix} \text{ mod } 26$$

$$= \begin{pmatrix} 77 & 126 \\ 105 & 49 \end{pmatrix} \text{ mod } 26 \qquad = \begin{pmatrix} 25 & 22 \\ 1 & 23 \end{pmatrix}$$

Hill Cipher



Plaintext →	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z
Ciphertext →	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
Value →	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25

Cipher text = APADJTFTWLFJ

$$P = K^{-1} * C \bmod 26 = \begin{pmatrix} 25 & 22 \\ 1 & 23 \end{pmatrix} \begin{pmatrix} 0 \\ 15 \end{pmatrix}$$

$=25*0 +22*15 = 330 \bmod 26 = 18 =$ S

$1*0 +23 *15 = 345 \text{ mode } 26 = 7 =$ H

Hill Cipher

Plaintext →	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z
Ciphertext →	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
Value →	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25

Plain Text = SAF EME SSA GES

Cipher text = HDS IOE YQO CAA

$P = K^{-1} * C \bmod 26$

Find out inverse matrix of given key matrix.

$$K^{-1} = \frac{1}{|K|} * K_{adj}$$

Hill Cipher

Plaintext →	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z
Ciphertext →	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
Value →	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25

Cipher text = HDS IOE YQO CAA

Find out inverse matrix of given key matrix.

$$K^{-1} = \frac{1}{|K|} * K_{adj}$$

$$K = \begin{pmatrix} 2 & 8 & 15 \\ 7 & 4 & 17 \\ 8 & 13 & 6 \end{pmatrix}$$

$$|K| = \begin{vmatrix} a & b & c \\ d & e & f \\ g & h & i \end{vmatrix} = a\begin{vmatrix} e & f \\ h & i \end{vmatrix} - b\begin{vmatrix} d & f \\ g & i \end{vmatrix} + c\begin{vmatrix} d & e \\ g & h \end{vmatrix}$$

$$= a(ei - fh) - b(di - fg) + c(dh - eg)$$

$$= aei - afh - bdi + bfg + cdh - ceg$$

$$= (aei + bfg + cdh) - (afh + bdi + ceg)$$

RAMAIAH Institute of Technology

Hill Cipher

Plaintext	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z
Ciphertext	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
Value	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25

$$|K| = \begin{vmatrix} a & b & c \\ d & e & f \\ g & h & i \end{vmatrix} = a\begin{vmatrix} e & f \\ h & i \end{vmatrix} - b\begin{vmatrix} d & f \\ g & i \end{vmatrix} + c\begin{vmatrix} d & e \\ g & h \end{vmatrix}$$

$$= a(ei - fh) - b(di - fg) + c(dh - eg)$$

= 2(4*6 -17*13) – 8 (7*6 -17*8) + 15(7*13 -4*8)

= 1243 mod 26 → 21

$$= \begin{pmatrix} 2 & 8 & 15 \\ 7 & 4 & 17 \\ 8 & 13 & 6 \end{pmatrix}$$

(matA^-1)*(det(matA))
==inverse
of matrix

$21^{-1} \bmod 26 = ?$
$21 (?) \bmod 26 = 1$
$21(1) \bmod 26 = 21$ not equal to 1
$21 (2) \bmod 26 = 42$ not equal to 1
.
. .
$21(5) \bmod 26 = 1$

So, $21^{-1} \bmod 26$

$$K^{-1} = \frac{1}{|D|} \text{adj}\,(K)$$

$$D^{-1}\,\text{adj}\,(K) = \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & i \end{bmatrix}^{-1}$$

$$= \frac{1}{|D|} \begin{bmatrix} +(ei - fh) & -(di - fg) & +(dh - eg) \\ -(bi - ch) & +(ai - cg) & -(ah - bg) \\ +(bf - ce) & -(af - cd) & +(ae - bd) \end{bmatrix}^{T}$$

Hill Cipher

$$K_{adj} = \begin{pmatrix} 2 & 8 & 15 \\ 7 & 4 & 17 \\ 8 & 13 & 6 \end{pmatrix}$$

$$= \begin{pmatrix} 4*6 - 17*13 & 7*6 - 17*8 & 7*13 - 4*8 \\ 8*6 - 15*13 & 2*6 - 15*8 & 2*13 - 8*8 \\ 8*17 - 15*4 & 2*17 - 15*7 & 2*4 - 8*7 \end{pmatrix}$$

$$\begin{pmatrix} -197 & -94 & 59 \\ 147 & -108 & 38 \\ 76 & 71 & -48 \end{pmatrix} \quad \begin{pmatrix} + & - & + \\ - & + & - \\ + & - & + \end{pmatrix}$$

$$\begin{pmatrix} -197 & 94 & 59 \\ 147 & -108 & 38 \\ 76 & 71 & -48 \end{pmatrix}$$

RAMAIAH Institute of Technology

Hill Cipher

$$\begin{pmatrix} -197 & 94 & 59 \\ 147 & -108 & 38 \\ 76 & 71 & -48 \end{pmatrix}$$

Take transpose

$$\begin{pmatrix} -197 & 147 & 76 \\ 94 & -108 & 71 \\ 59 & 38 & -48 \end{pmatrix}$$

$$\begin{pmatrix} 11 & 147 & 76 \\ 94 & 22 & 38 \\ 59 & 71 & 4 \end{pmatrix}$$

Repeatedly add +26 to make negative to positive

Hill Cipher

$$= 5 * \begin{pmatrix} 11 & 147 & 76 \\ 94 & 22 & 38 \\ 59 & 71 & 4 \end{pmatrix}$$

$$\begin{pmatrix} 55 & 735 & 380 \\ 470 & 110 & 355 \\ 295 & 190 & 20 \end{pmatrix} \quad \text{Mod } 26 \rightarrow \quad \begin{pmatrix} 3 & 7 & 16 \\ 2 & 6 & 17 \\ 9 & 8 & 20 \end{pmatrix}$$

$$P = K^{-1} C \bmod 26 = \begin{bmatrix} 3 & 7 & 16 \\ 2 & 6 & 17 \\ 9 & 8 & 20 \end{bmatrix} \begin{bmatrix} 7 \\ 3 \\ 18 \end{bmatrix} \bmod 26$$

$$= \begin{bmatrix} 3(7) + 7(3) + 16 \\ 2(7) + 6(3) + 17 \\ 9(7) + 8(3) + 20 \end{bmatrix} = \begin{bmatrix} 330 \\ 338 \\ 447 \end{bmatrix} \bmod 26 = \begin{bmatrix} 18 \\ 0 \\ 5 \end{bmatrix} = \begin{bmatrix} s \\ a \\ f \end{bmatrix}.$$

$$= \begin{bmatrix} 330 \\ 338 \\ 447 \end{bmatrix} \bmod 26 = \begin{bmatrix} 18 \\ 0 \\ 5 \end{bmatrix} = \begin{bmatrix} s \\ a \\ f \end{bmatrix}.$$

$$P = K^{-1} C \bmod 26 = \begin{bmatrix} 3 & 7 & 16 \\ 2 & 6 & 17 \\ 9 & 8 & 20 \end{bmatrix} \begin{bmatrix} 8 \\ 14 \\ 4 \end{bmatrix} \bmod 26 = \begin{bmatrix} 3(8) + 7(14) + 16(4) \\ 2(8) + 6(14) + 17(4) \\ 9(8) + 8(14) + 20(4) \end{bmatrix} \bmod 26 = \begin{bmatrix} 186 \\ 168 \\ 264 \end{bmatrix} \bmod 26 = \begin{bmatrix} 4 \\ 12 \\ 4 \end{bmatrix} = \begin{bmatrix} e \\ m \\ e \end{bmatrix}.$$

$$P = K^{-1} C \bmod 26 = \begin{bmatrix} 3 & 7 & 16 \\ 2 & 6 & 17 \\ 9 & 8 & 20 \end{bmatrix} \begin{bmatrix} 24 \\ 16 \\ 14 \end{bmatrix} \bmod 26 = \begin{bmatrix} 3(24) + 7(16) + 16(14) \\ 2(24) + 6(16) + 17(14) \\ 9(24) + 8(16) + 20(14) \end{bmatrix} \bmod 26 = \begin{bmatrix} 18 \\ 18 \\ 0 \end{bmatrix} = \begin{bmatrix} s \\ s \\ a \end{bmatrix}.$$

$$P = K^{-1} C \bmod 26 = \begin{bmatrix} 3 & 7 & 16 \\ 2 & 6 & 17 \\ 9 & 8 & 20 \end{bmatrix} \begin{bmatrix} 2 \\ 0 \\ 0 \end{bmatrix} \bmod 26 = \begin{bmatrix} 3(2) + 7(0) + 16(0) \\ 2(2) + 6(0) + 17(0) \\ 9(2) + 8(0) + 20(0) \end{bmatrix} \bmod 26 = \begin{bmatrix} 6 \\ 4 \\ 18 \end{bmatrix} = \begin{bmatrix} g \\ e \\ s \end{bmatrix}.$$

Encrypt the plaintext “attack”, using Hill cipher for the given key = $\begin{bmatrix} 2 & 3 \\ 3 & 6 \end{bmatrix}$.

Ciphertext: “FKMFIO”.

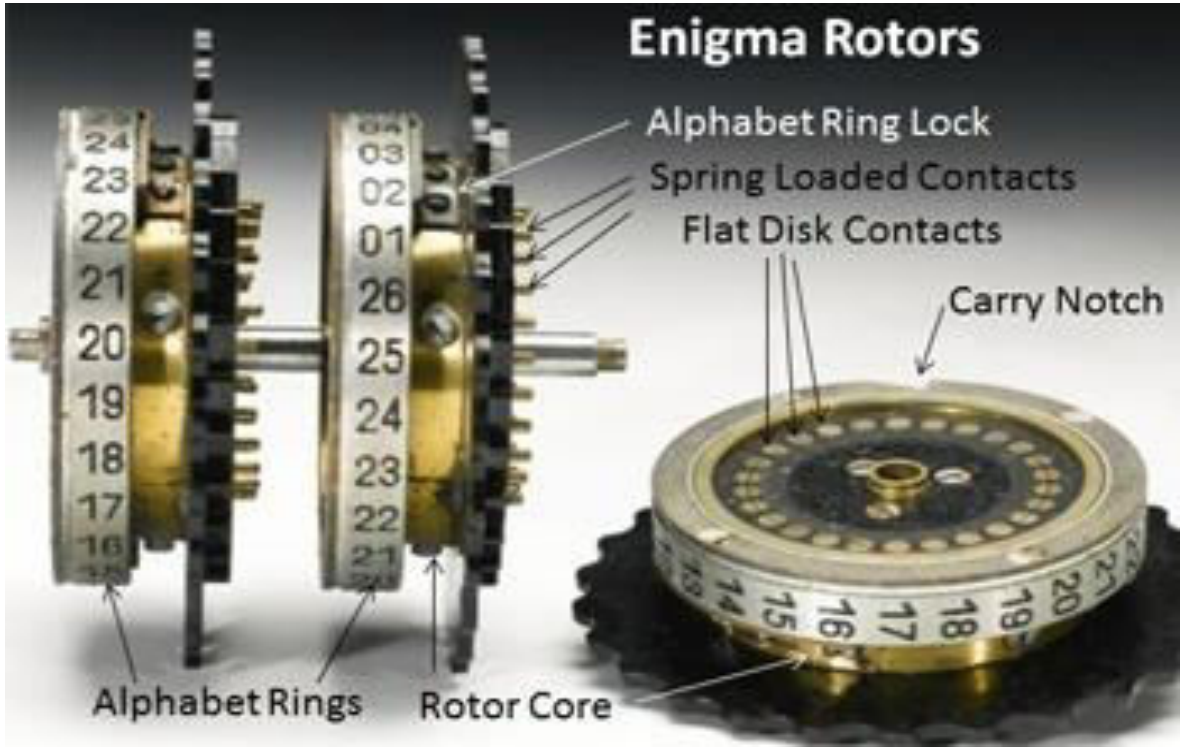
Encrypt the message **"retreat now"** using the keyphrase **back up** and a 3 x 3 matrix.

$$\begin{pmatrix} r \\ e \\ t \end{pmatrix} \begin{pmatrix} r \\ e \\ a \end{pmatrix} \begin{pmatrix} t \\ n \\ o \end{pmatrix} \begin{pmatrix} w \\ x \\ x \end{pmatrix}$$

$$\begin{pmatrix} B & A & C \\ K & U & P \\ A & B & C \end{pmatrix} \quad \begin{pmatrix} 1 & 0 & 2 \\ 10 & 20 & 15 \\ 0 & 1 & 2 \end{pmatrix}$$

ROTOR CIPHER

A rotor is a thick disk that has near its outer circumference on both sides as many electric contacts as letters in the alphabet (usually 26—early versions of the Enigma used 28 or 29 letters).

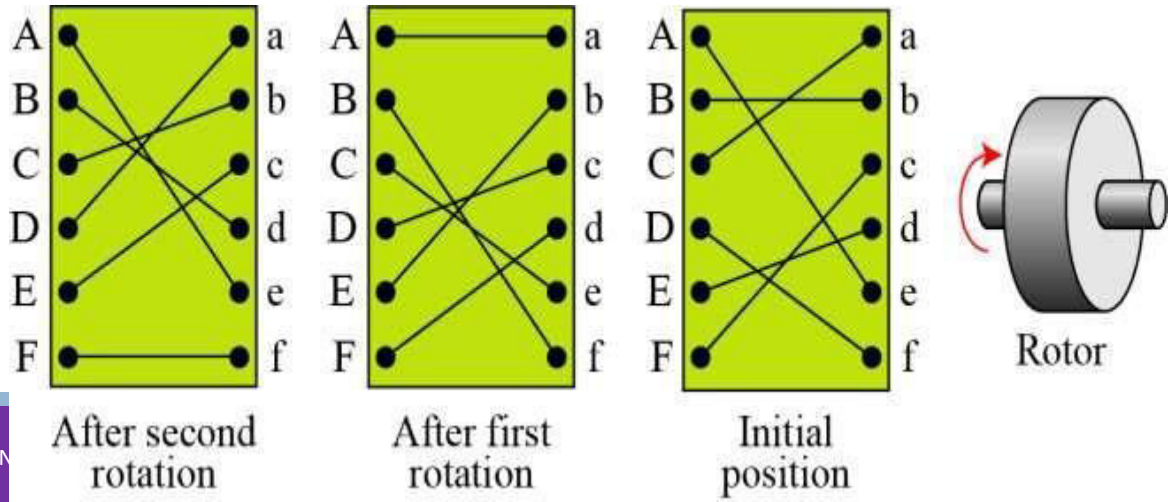


RAMAIAH
Institute of Technology

ROTOR CIPHER

- Rotor uses only 6 letters
- Initial setting is key agreed between sender and receiver
- First character is encrypted using initial position
- Second character after first rotation
- Third character after second rotation
- Example : bee → BCA

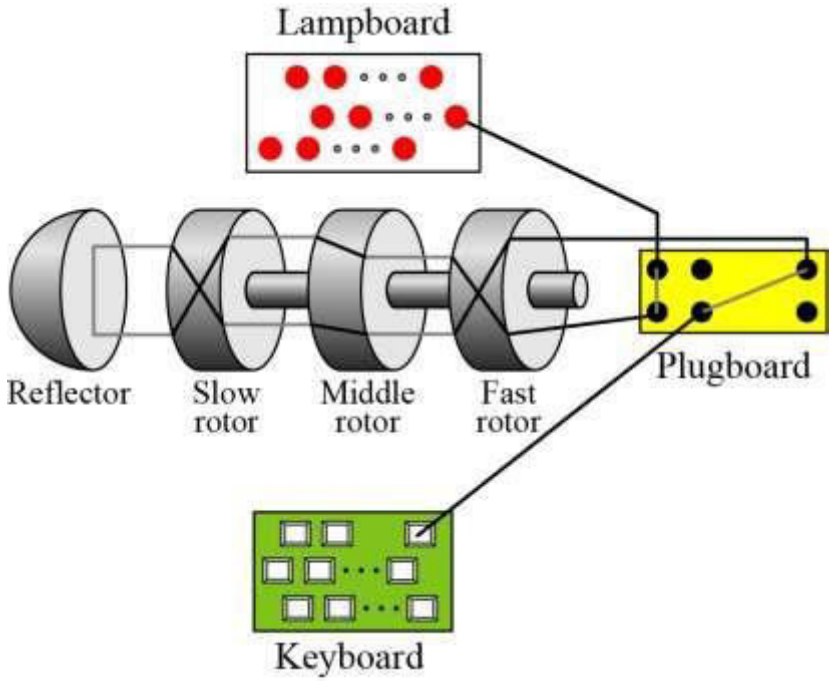
A rotor cipher



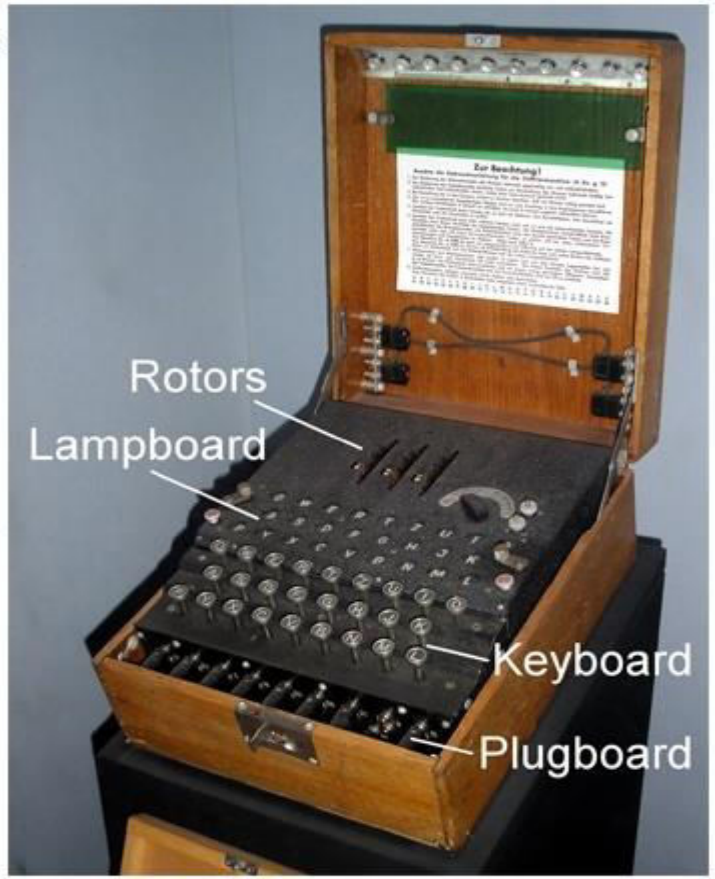
ROTOR CIPHER

Main components of Enigma machine

1. Keyboard = 26keys
2. Lampboard =26 lamps
3. Plugboard = 26plugs
4. Three rotors
5. Reflector



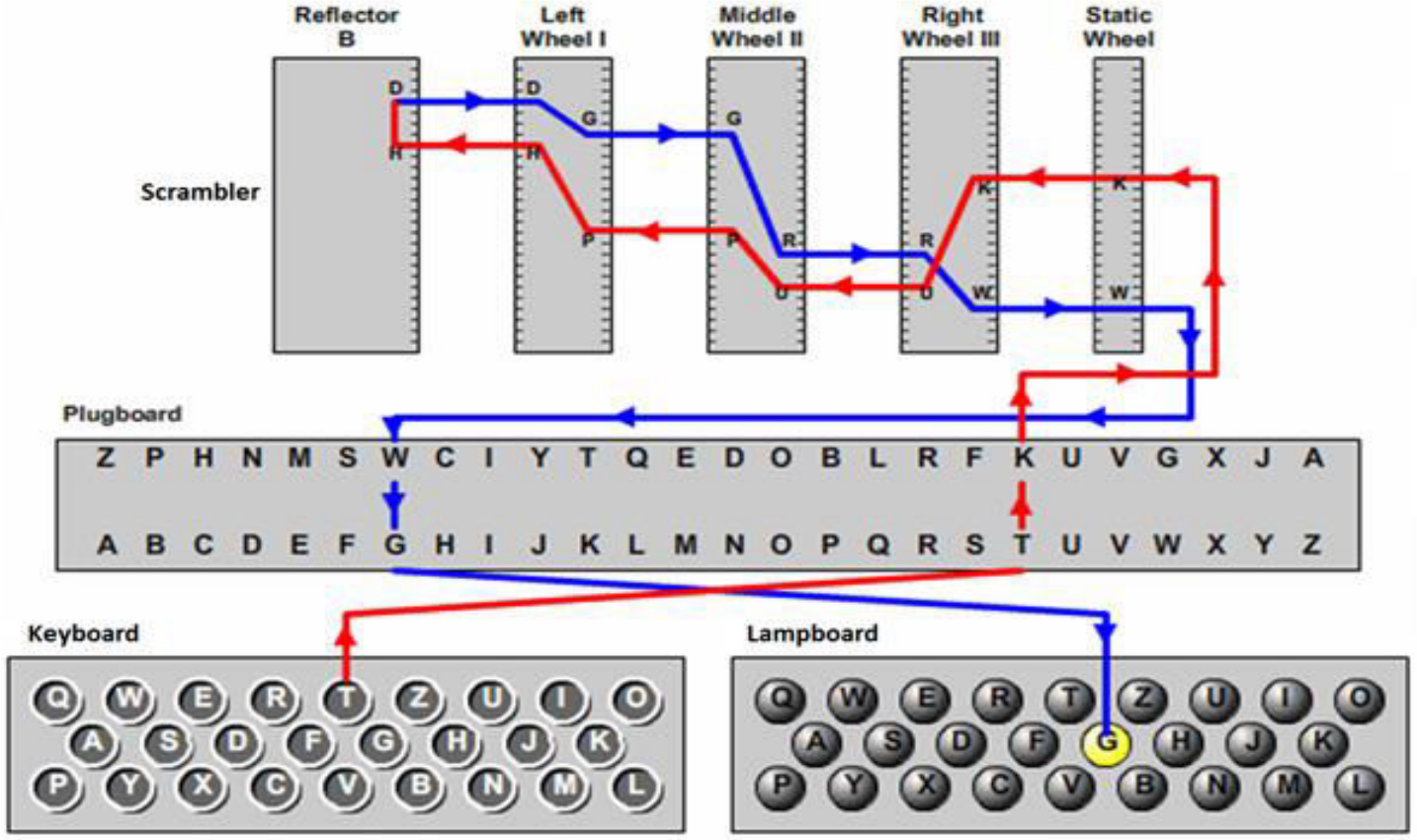
The Enigma Ciphertext Machine



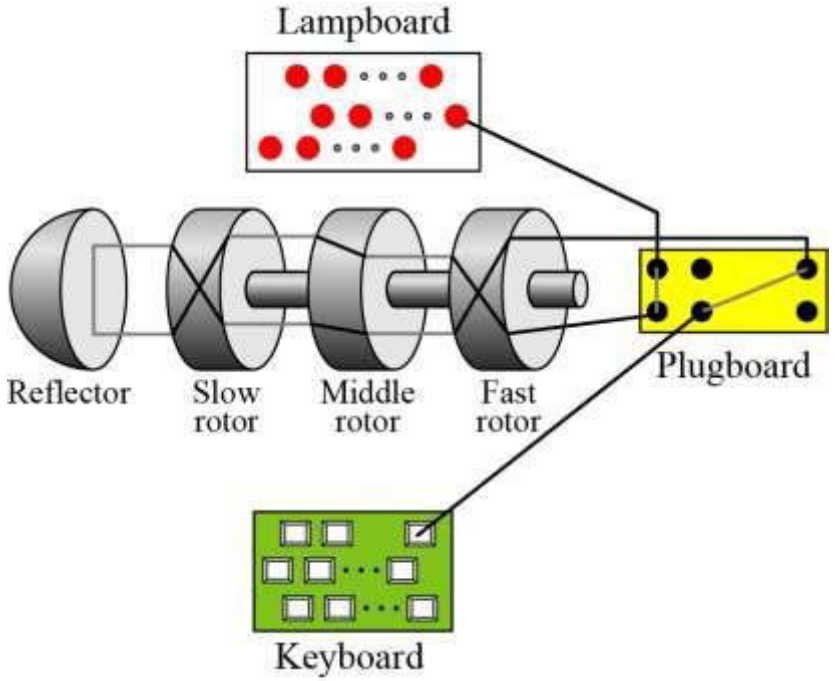
ROTOR CIPHER

- **Keyboard** (input)
- **Lampboard** (output)
- **Rotors** (polyalphabetic encryption)
  - 3 - 4 rotors (depending on Enigma type)
  - 1 reflector
  - 26 contacts at both sides
  - Wired unregularly
  - Turns one step at each letter
  - Turnover is based on ring setting
  - Exchangeable
- **Plugboard** (monoalphabetic encryption)
  - Interchanges letters

ROTOR CIPHER



A schematic of the Enigma machine



ROTOR CIPHER

To use Engima machine , a code book is published that gives several settings for each day

a. 3 rotor to be chosen, out of 5 available
b. The order in which rotor to be installed
c. Setting for plugboard
d. A three letter code for the day

ROTOR CIPHER

Procedure for Encrypting message

1. Set starting position of rotor to code of the day. For example code was “HUA”
2. Choose a random 3 letter code such as ACF

   Encrypt **ACFACF**(repeated code) using code from step1

   Encrypted code is OPNABT
3. Set the starting position to OPN(half of encrypted code)
4. Append encrypted code to message →ACFOPNABT
5. Encrypt the message →ACFOPNABT. Send the encrypted message

ROTOR CIPHER

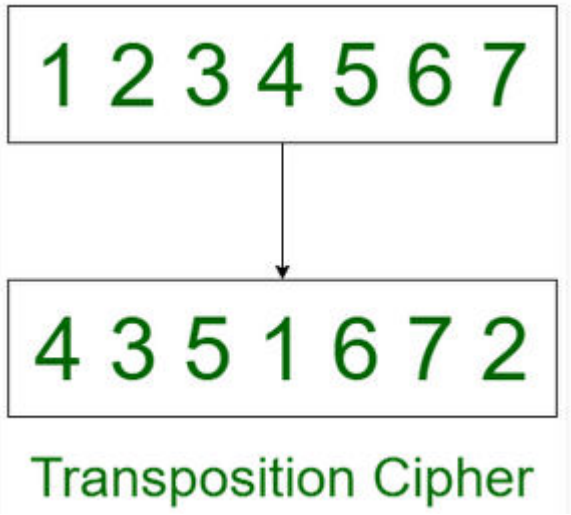
Procedure for Decrypting message

1. Receive the message and separate the first six letters
2. Set the starting position of the rotor to the code of the day
3. Decrypt the first six letter using initial setting in step2
4. Set the position of the rotor to the first half of the decrypted code
5. Decrypt the message (without the first six letter)

TRANSPOSITION CIPHERS

Transposition Cipher rearranges the position of the characters of plain text.

It changes the position of the character but it does not change the identity of the character.



TRANSPOSITION CIPHERS

A transposition cipher does not substitute one symbol for another, instead it changes the location of the symbols.

A transposition cipher reorders symbols.

1. Keyless Transposition Ciphers
2. Keyed Transposition Ciphers
3. Combining Two Approaches

Keyless Transposition Ciphers

Simple transposition ciphers, which were used in the past, are keyless.

Two Methods are

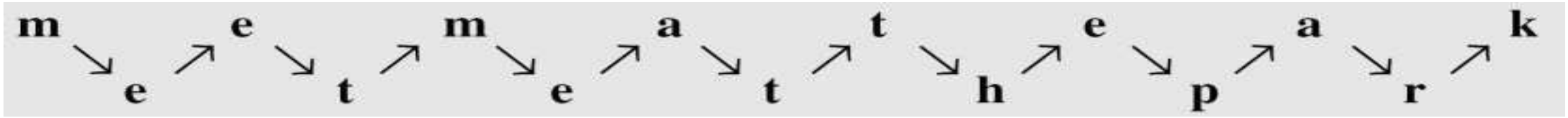
1. Text is written into table column by column and transmit row by row(Rail Fence cipher)
2. Text is written into table row by row and transmit column by column

Keyless Transposition Ciphers

Rail fence cipher

PT is arranged in two line as a zigzag pattern(Column by column)

For example: “Meet me at the park”



8

7

The ciphertext is created reading the pattern row by row.

Ciphertext “MEMATEAKETETHPR”.

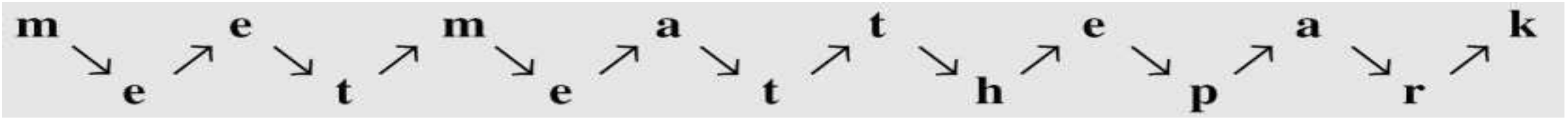
RAMAIAH
Institute of Technology

Keyless Transposition Ciphers

Rail fence cipher

Ciphertext "MEMATEAKETETHPR"

Receiver divides into half (first half form the first row and second half second row) and reads in zigzag



The ciphertext is created reading the pattern row by row.

TRANSPOSITION CIPHERS

Alice and Bob can agree on the number of columns.

Alice writes the plaintext, row by row, in a table of four columns.

For example: “Meet me at the park”

m	e	e	t
m	e	a	t
t	h	e	p
a	r	k	

Ciphertext “MMTAEEHREAEKTTP”.

Meet me at the park MMTAEEHREAEKTTP

The following shows the permutation of each character in the plaintext into the ciphertext based on the positions.

01	02	03	04	05	06	07	08	09	10	11	12	13	14	15
↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
01	05	09	13	02	06	10	13	03	07	11	15	04	08	12

The second character in the plaintext has moved to the fifth position in the ciphertext; the third character has moved to the ninth position; and so on.

Although the characters are permuted, there is a pattern in the permutation: (01, 05, 09, 13), (02, 06, 10, 13), (03, 07, 11, 15), and (08, 12).

In each section, the difference between the two adjacent numbers is 4.

Keyed Transposition Ciphers

- Divide the plaintext into groups of predetermined size, called blocks, and then use a key to permute the characters in each block separately.
- Alice needs to send the message "Enemy attacks tonight" to Bob.
- Alice and Bob agrees with block size =5

e n e m y a t t a c k s t o n i g h t z

- The key used for encryption and decryption is a permutationkey, which shows how the character are permuted.

Keyed Transposition Ciphers

- Divide the plaintext into groups of predetermined size, called blocks, and then use a key to permute the characters in each block separately.
- Alice needs to send the message “Enemy attacks tonight” to Bob.
- Alice and Bob agrees with block size =5

e n e m y a t t a c k s t o n i g h t z

RAMAIAH
Institute of Technology

Keyed Transposition Ciphers

e n e m y a t t a c k s t o n i g h t z

Encryption ↓

3	1	4	5	2
1	2	3	4	5

↑ Decryption

The permutation yields

E E M Y N T A A C T T K O N S H I T Z G

Keyed Transposition Ciphers

Encryption ↓

3	1	4	5	2
1	2	3	4	5

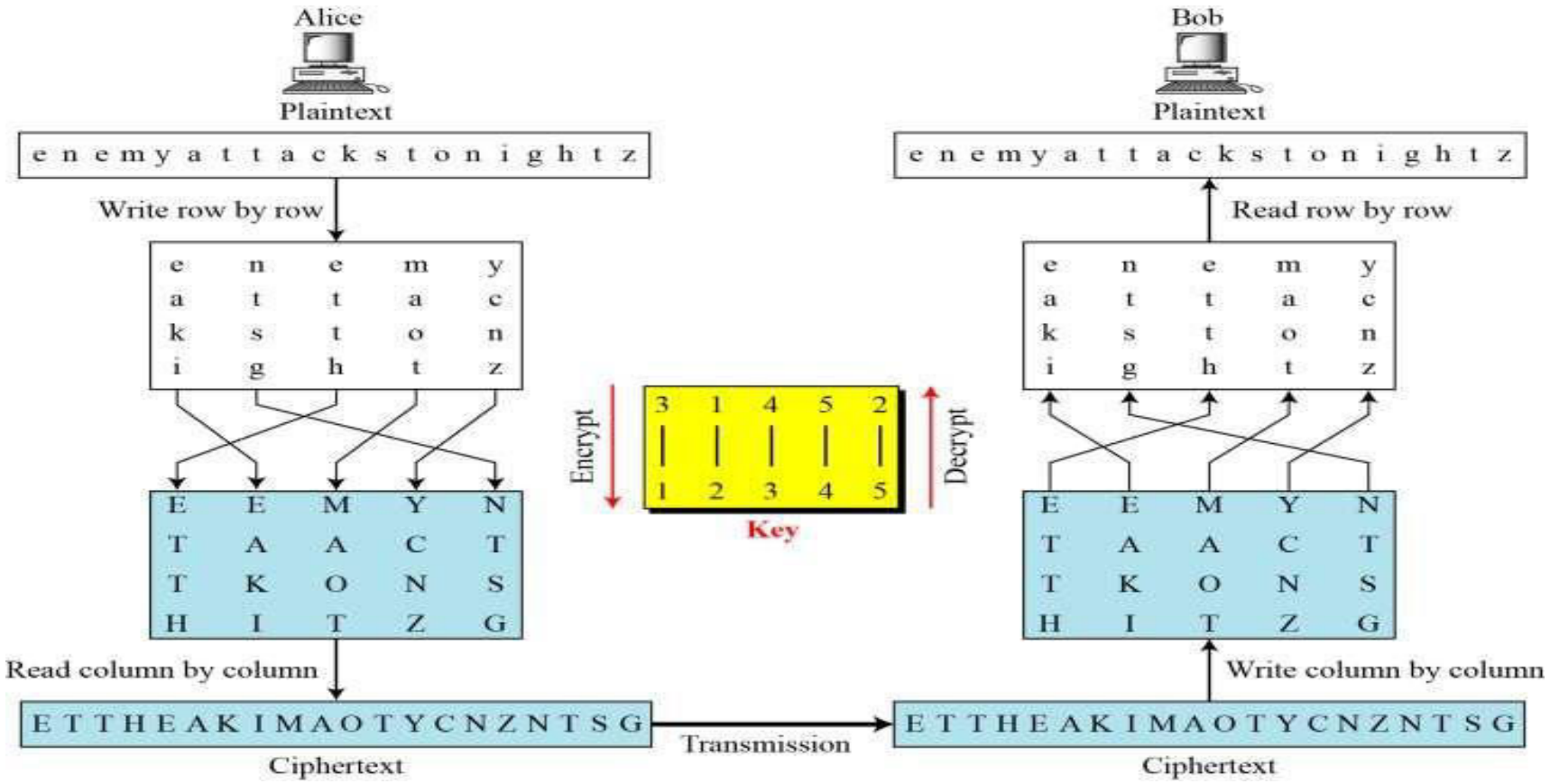
↑ Decryption

The permutation yields

E E M Y N T A A C T T K O N S H I T Z G

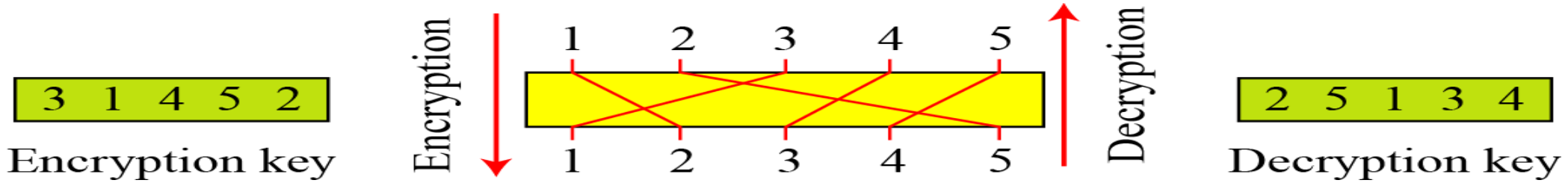
e n e m y a t t a c k s t o n i g h t z

Combining Two Approaches



Keys

A single key was used in two directions for the column exchange: downward for encryption, upward for decryption. It is customary to create two keys.



Encryption/decryption keys in transpositional ciphers

Encryption ↓

3	1	4	5	2
1	2	3	4	5

↑ Decryption

STREAM AND BLOCK CIPHERS

The literature divides the symmetric ciphers into two broad categories:

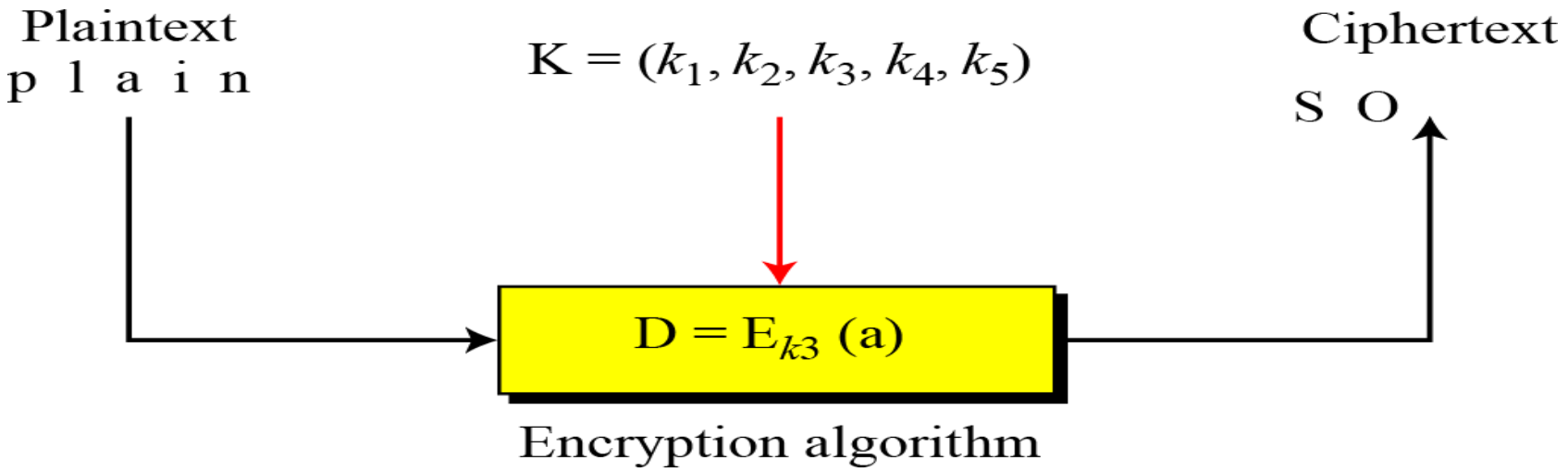
- Stream ciphers
- Block ciphers

STREAM CIPHERS

Stream ciphers - Call the plaintext stream P, the ciphertext stream C, and the key stream K.

$$P = P_1P_2P_3, \ldots \qquad C = C_1C_2C_3, \ldots \qquad K = (k_1, k_2, k_3, \ldots)$$

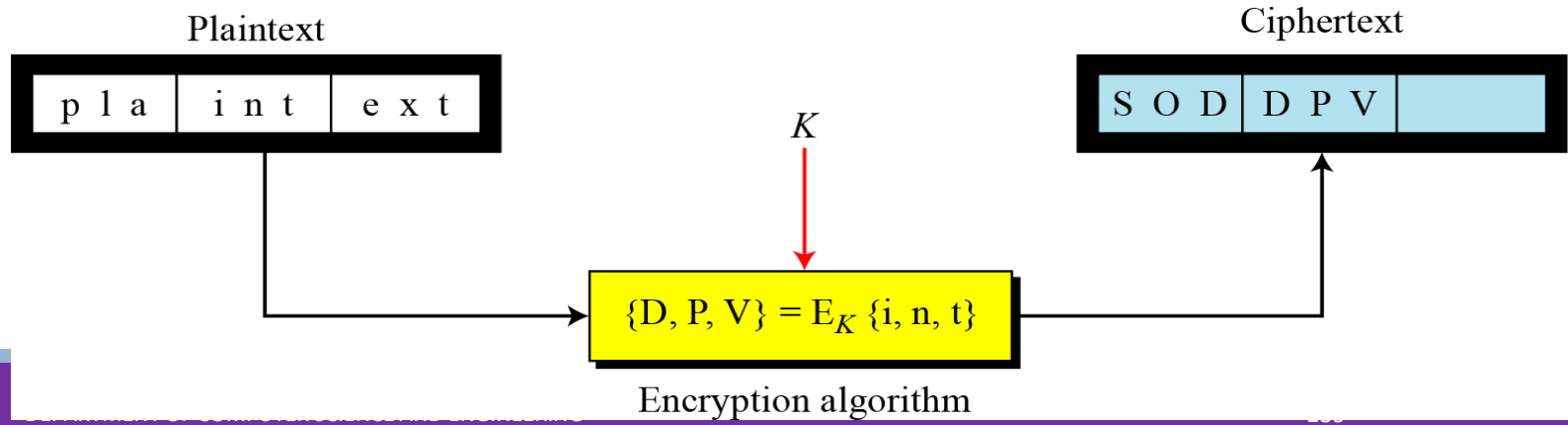
$$C_1 = E_{k1}(P_1) \qquad C_2 = E_{k2}(P_2) \qquad C_3 = E_{k3}(P_3) \ldots$$



Block Ciphers

In a block cipher, a group of plaintext symbols of size m (m > 1) are encrypted together creating a group of ciphertext of the same size.

A single key is used to encrypt the whole block even if the key is made of multiple values.



Block Cipher	Stream Cipher
Processing or encoding of the plain text is done as a fixed length block one by one. A block for example could be 64 or 128 bits in size.	Processing or encoding of plain text is done bit by bit. The block size here is simply one bit.
The same key is used to encrypt each of the blocks	A different key is used to encrypt each of the bits.
A Pad added to short length blocks	Bits are processed one by one in as in a chain
Uses Symmetric Encryption and is NOT used in asymmetric encryption	High speed and low hardware complexity
Confusion factor: The key to the cipher text relationship could be really very complicated.	Key is often combined with an initialization vector
Diffusion Factor: output depends on the input in a very complex method.	Long period with no repetition
Most block ciphers are based on Feistel cipher in structure	Statistically random
Looks more like an extremely large substitution and Using the idea of a product cipher	Depends on a large key and Large liner complexity
More secure in most cases	Equally secure if properly designed
Usually more complex and slower in operation	Usually very simple and much faster
Examples of Block Cipher are: Lucifer / DES,IDEA, RC5, Blowfish etc.	Examples of Stream Cipher are: FISH, RC4, ISAAC, SEAL, SNOW etc.

UNIT 2

Data Encryption Standard (DES): (Chapter 6)

- Introduction
- DES Structure
- DES Analysis
- Security of DES

History

•In 1973, NIST published a request for proposals for a national symmetric-key cryptosystem.

•A proposal from IBM, a modification of a project called Lucifer, was accepted as DES.

•DES was published in the Federal Register in March 1975 as a draft of the Federal Information Processing Standard (FIPS).

DES Overview

The Data Encryption Standard (DES) is a symmetric-key block cipher published by the National Institute of Standards and Technology (NIST).

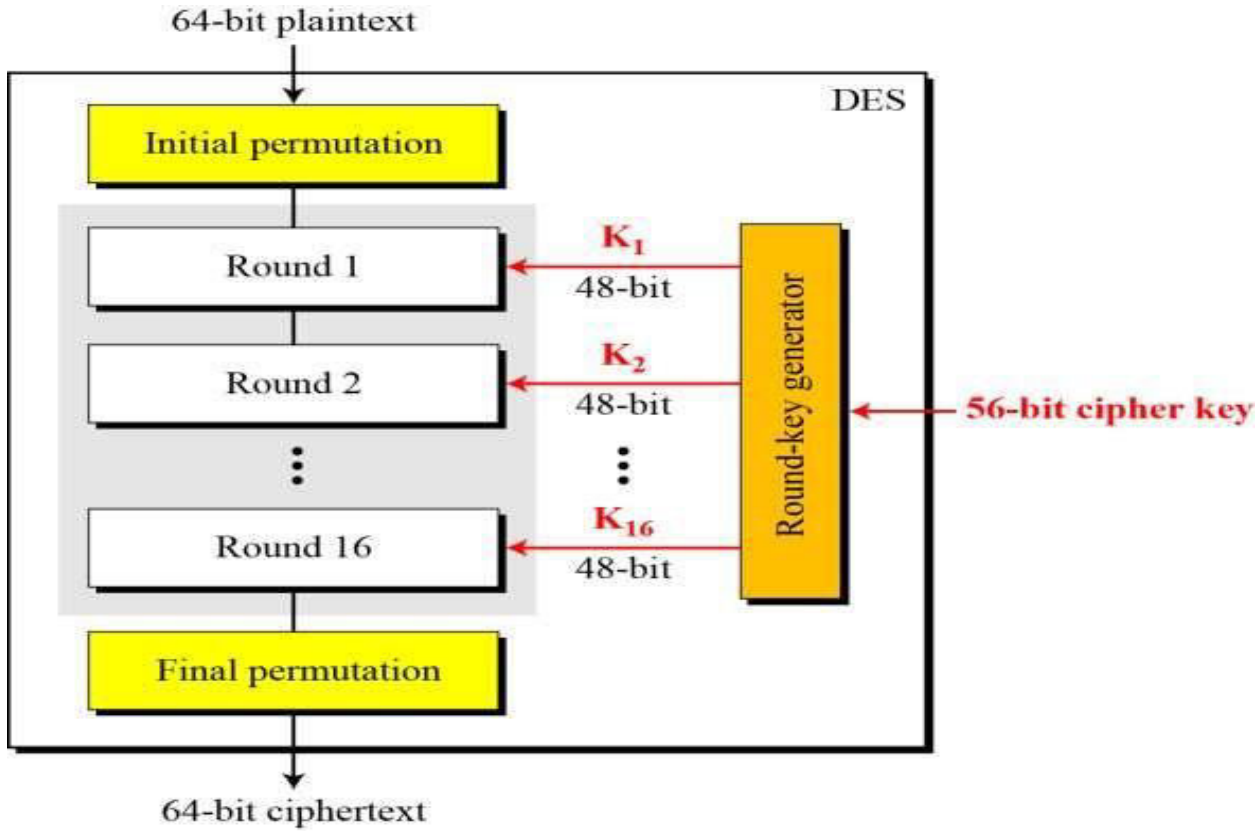
DES is a block cipher. The block size is 64-bit.

DES Structure

DES is an implementation of a Feistel Cipher.

It uses 16 round Feistel structure.

Key length is 64-bit, DES has an effective key length of 56 bits, since 8 of the 64 bits of the key are not used by the encryption algorithm



DES Structure

Two properties that a good cryptosystem should have to hinder statistical analysis:

1. Diffusion -If a single symbol in the plaintext is changed, several or all symbol in the ciphertext will also be changed
2. Confusion - If a single bit in the key is changed, most or all bits in the ciphertext will also be changed

Confusion = Substitution

a --> b

Caesar Cipher

Diffusion = Transposition or Permutation

abcd --> dacb

DES

DES Structure

DES uses a 56-bit key.

Actually, the initial key consists of 64 bits.

However, before the DES process even starts, every 8th bit of the key is discarded to produce a 56-bit key. That is bit positions 8, 16, 24, 32, 40, 48, 56, and 64 are discarded.

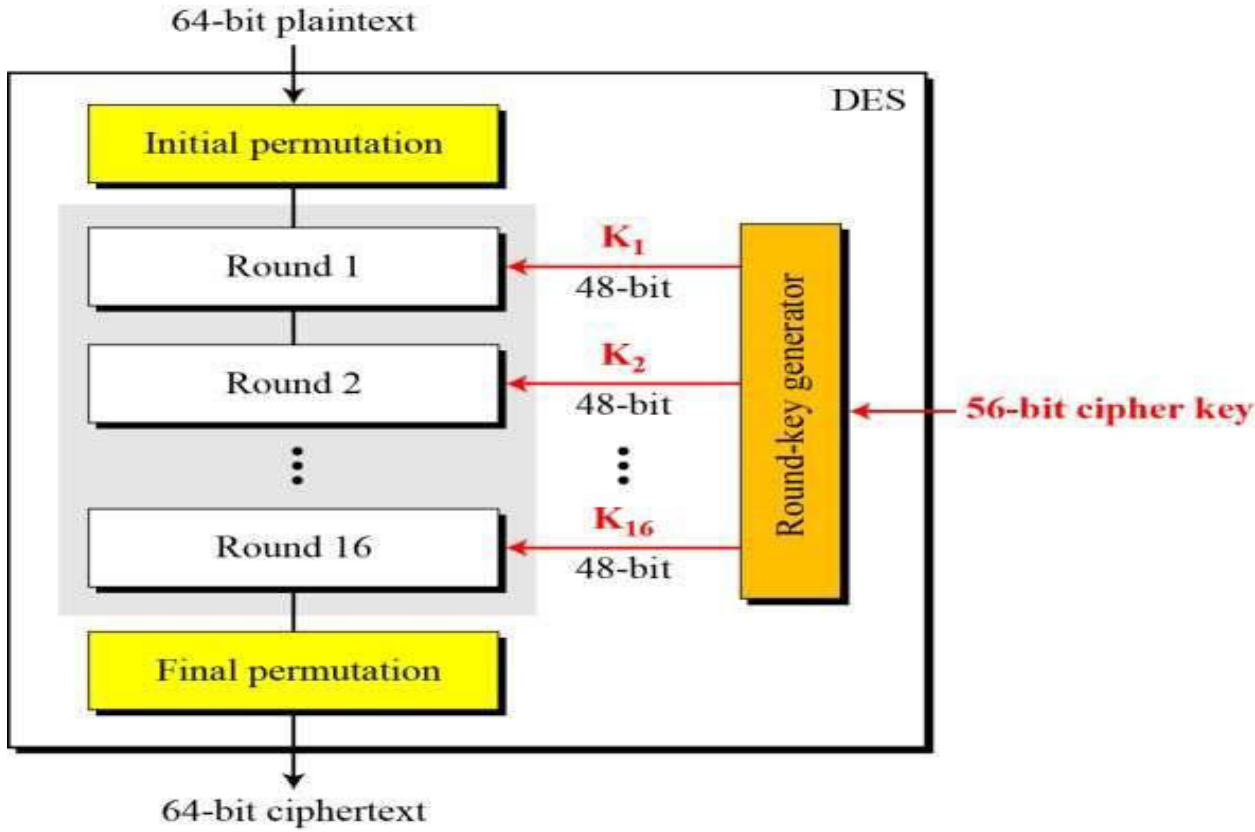
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64

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

DES Structure

DES is based on the Feistel Cipher

- Initial and final permutation
- Round function
- Round Key Generator



DES Structure

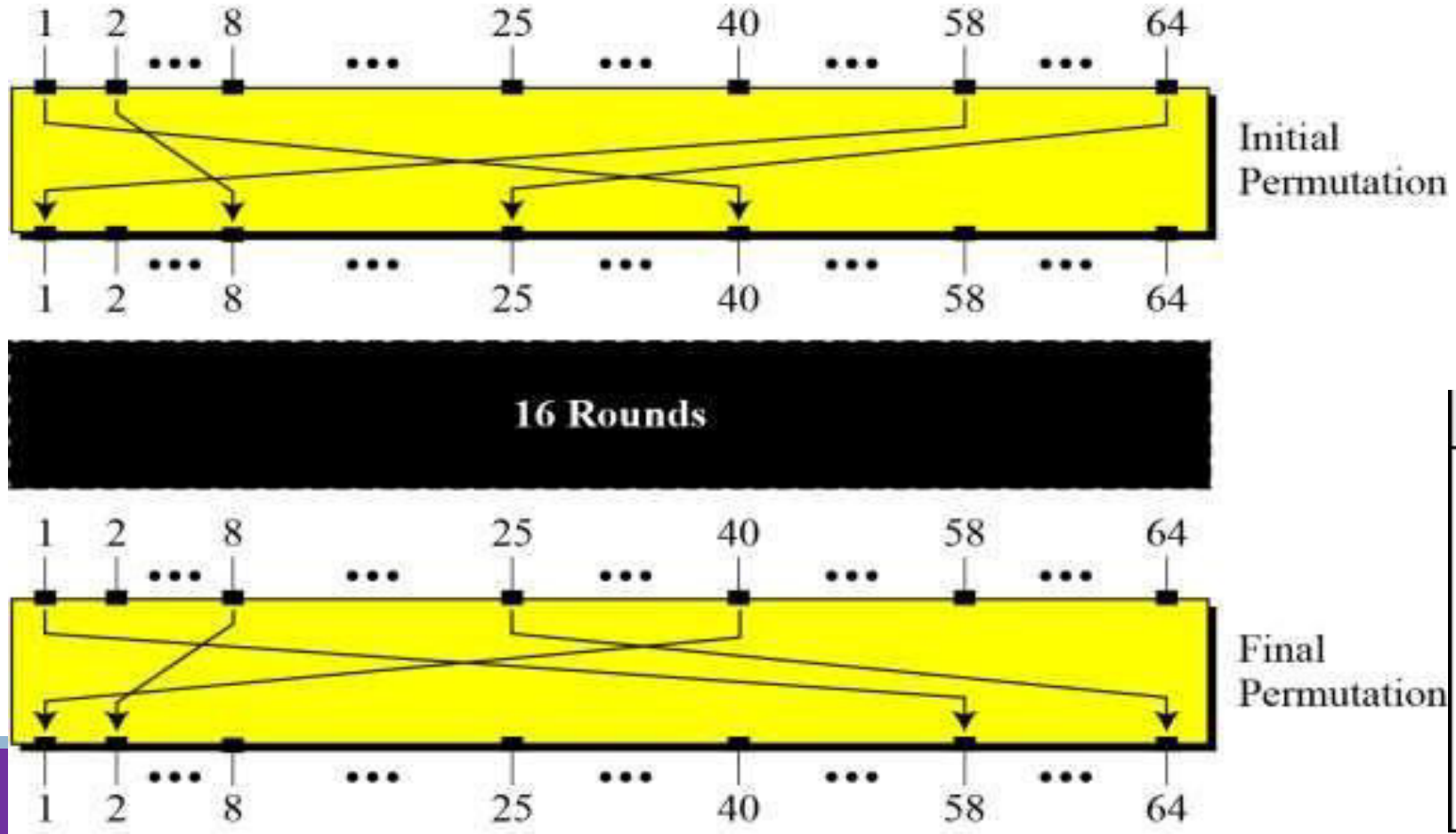
Initial and final permutation

- The initial permutation (IP) happens only once and it happens before the first round.
- Transposition in IP is done, Both are keyless and predetermined.
- IP replaces the first bit of the original plain text block with the 58th bit of the original plain text, the second bit with the 50th bit of the original plain text block, and so on.

RAMAIAH
Institute of Technology

DES Structure

Initial and final permutation step



Permutation Box

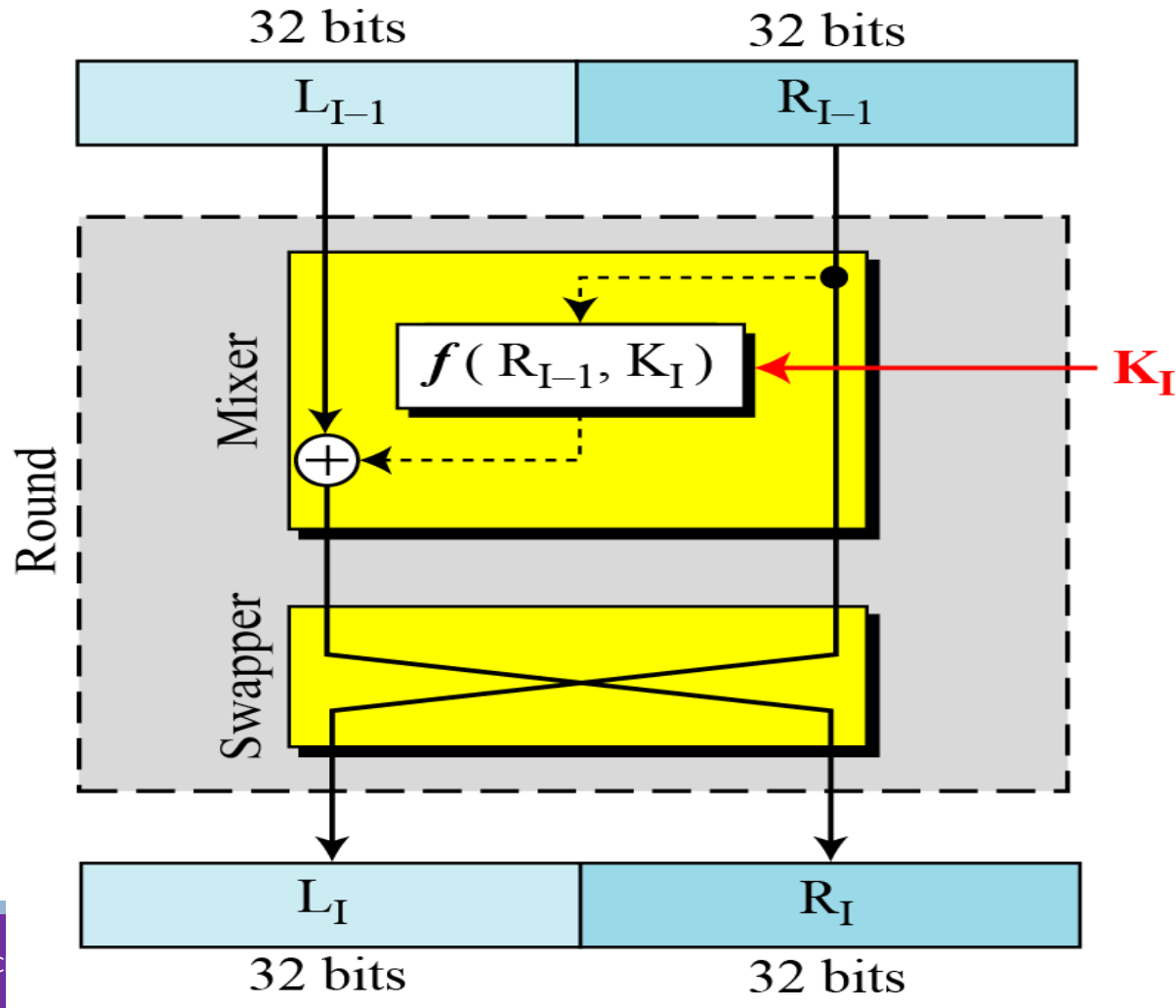
Initial Permutation							
58	50	42	34	26	18	10	02
60	52	44	36	28	20	12	04
62	54	46	38	30	22	14	06
64	56	48	40	32	24	16	08
57	49	41	33	25	17	09	01
59	51	43	35	27	19	11	03
61	53	45	37	29	21	13	05
63	55	47	39	31	23	15	07

Final Permutation							
40	08	48	16	56	24	64	32
39	07	47	15	55	23	63	31
38	06	46	14	54	22	62	30
37	05	45	13	53	21	61	29
36	04	44	12	52	20	60	28
35	03	43	11	51	19	59	27
34	02	42	10	50	18	58	26
33	01	41	09	49	17	57	25

DES Structure

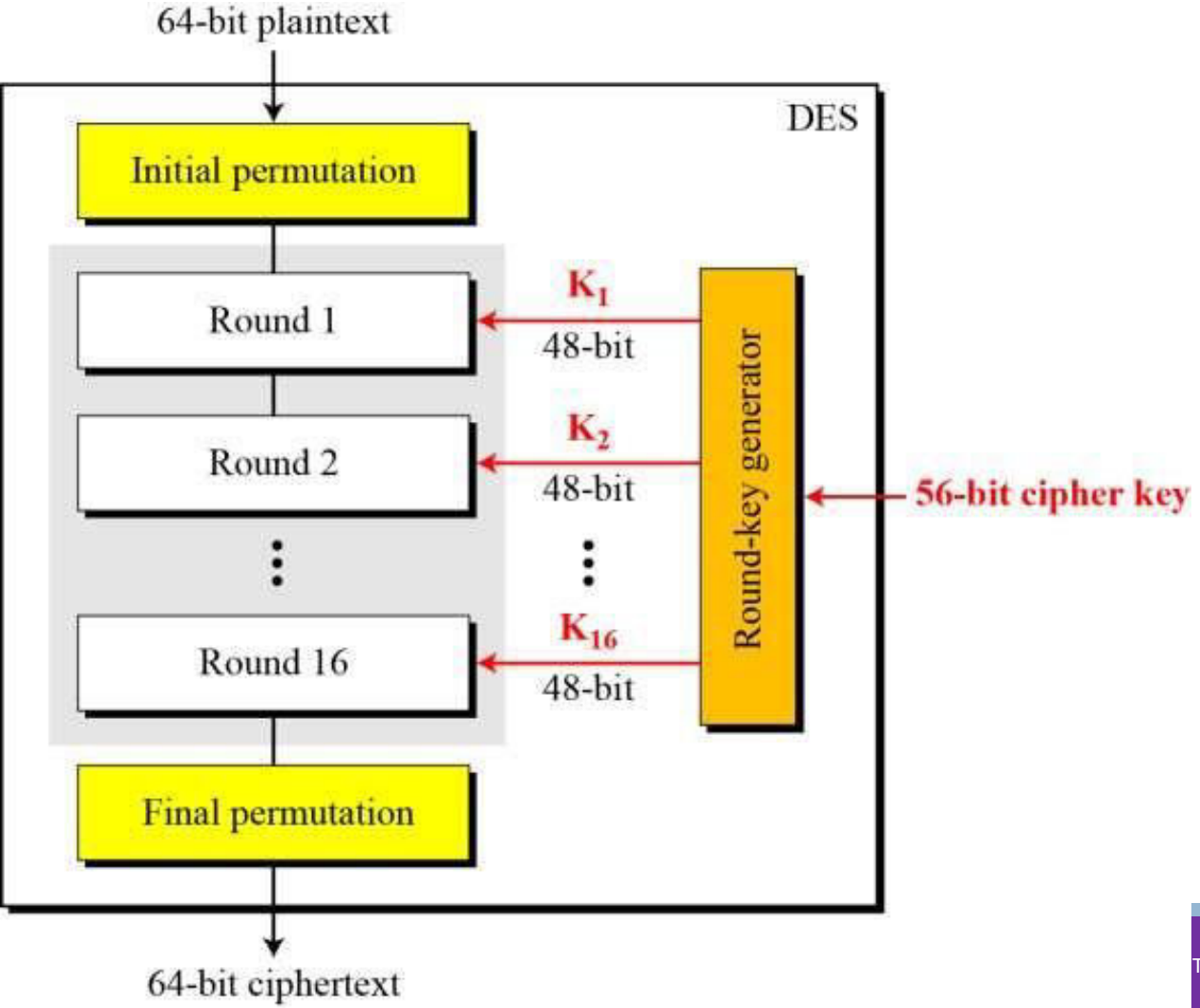
Round function

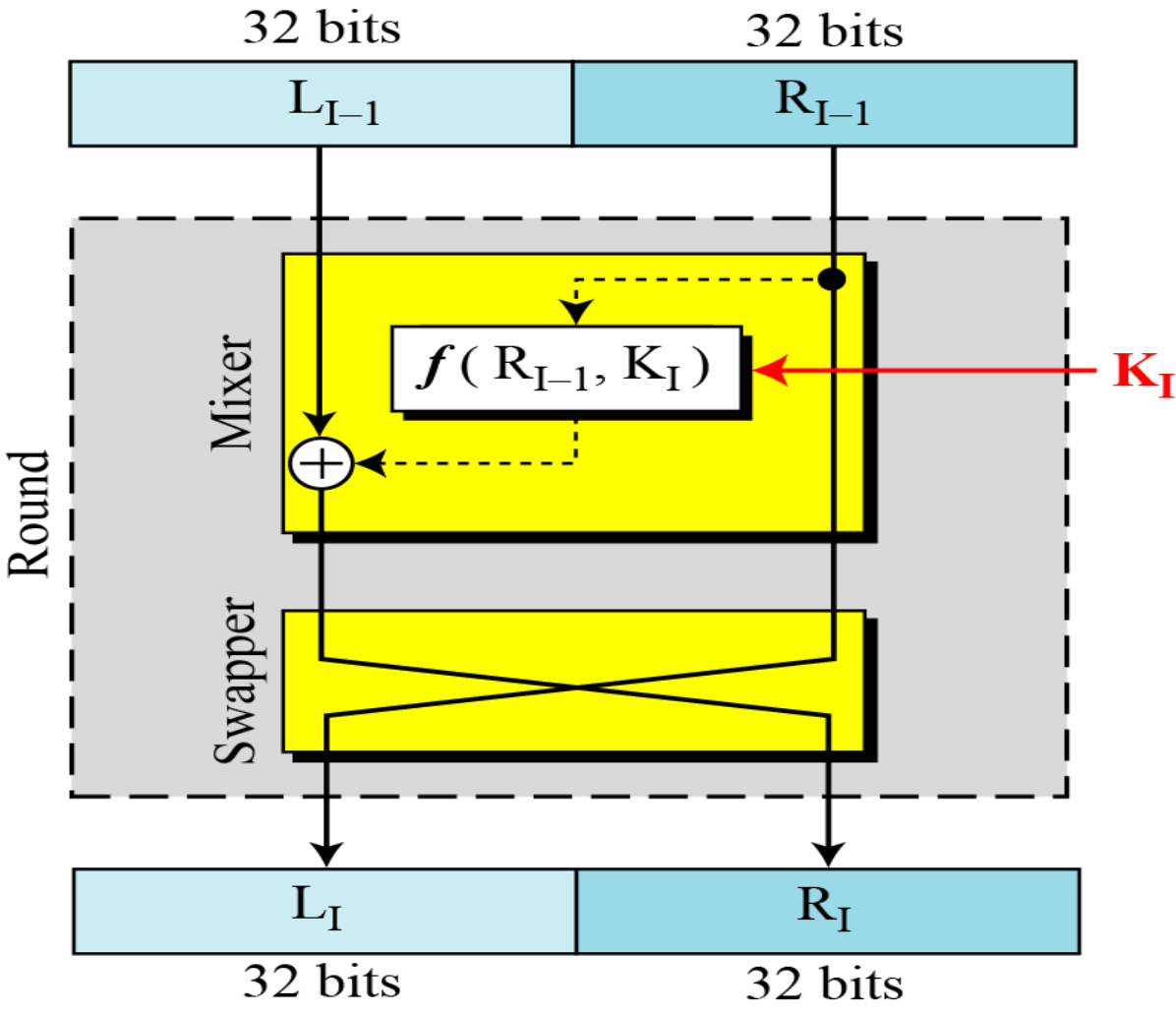
- DES uses 16 rounds
- Each round is a Feistel cipher is the DES function *f*.



RAMAIAH
Institute of Technology

DES Structure

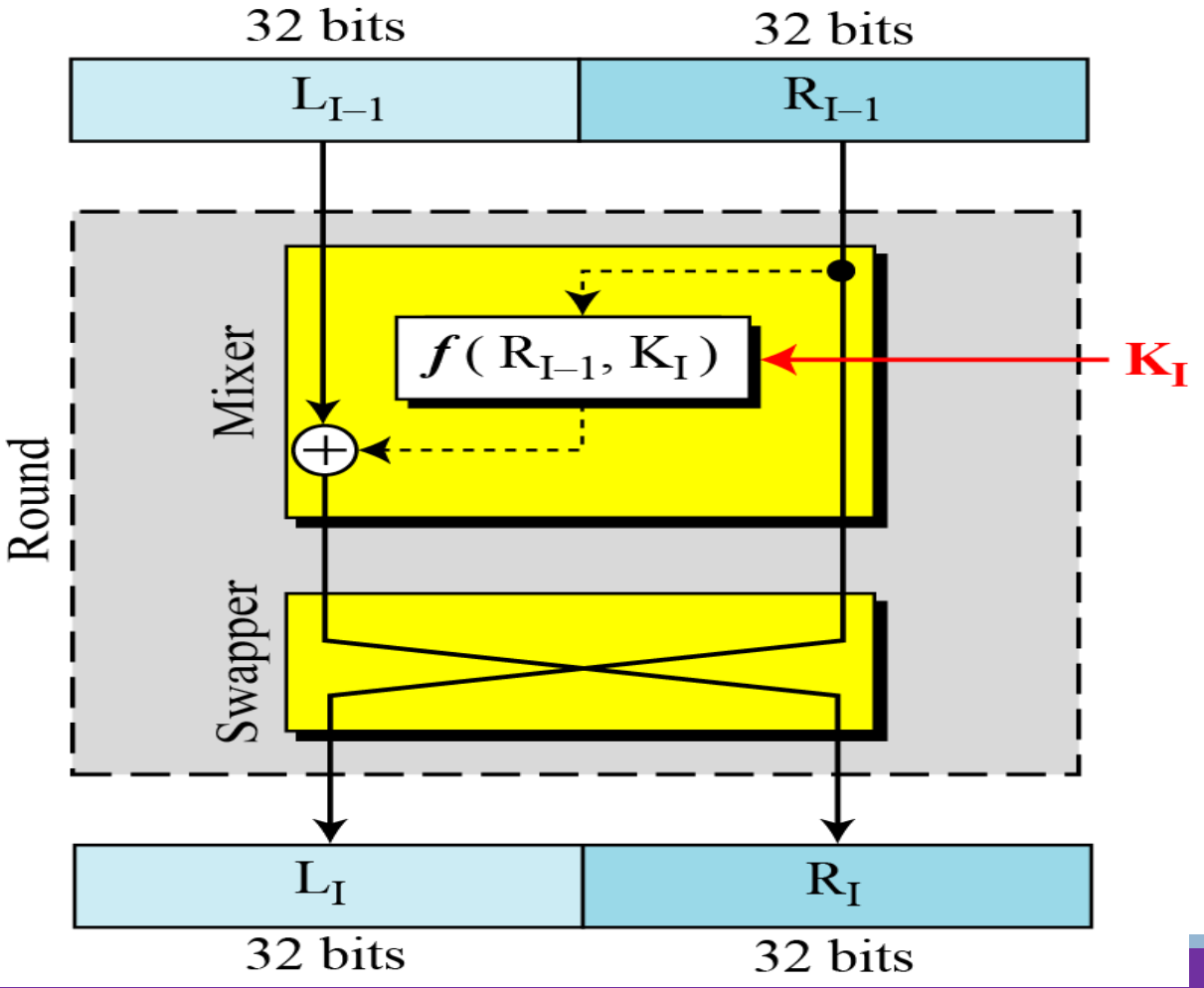




DES Structure

Round function

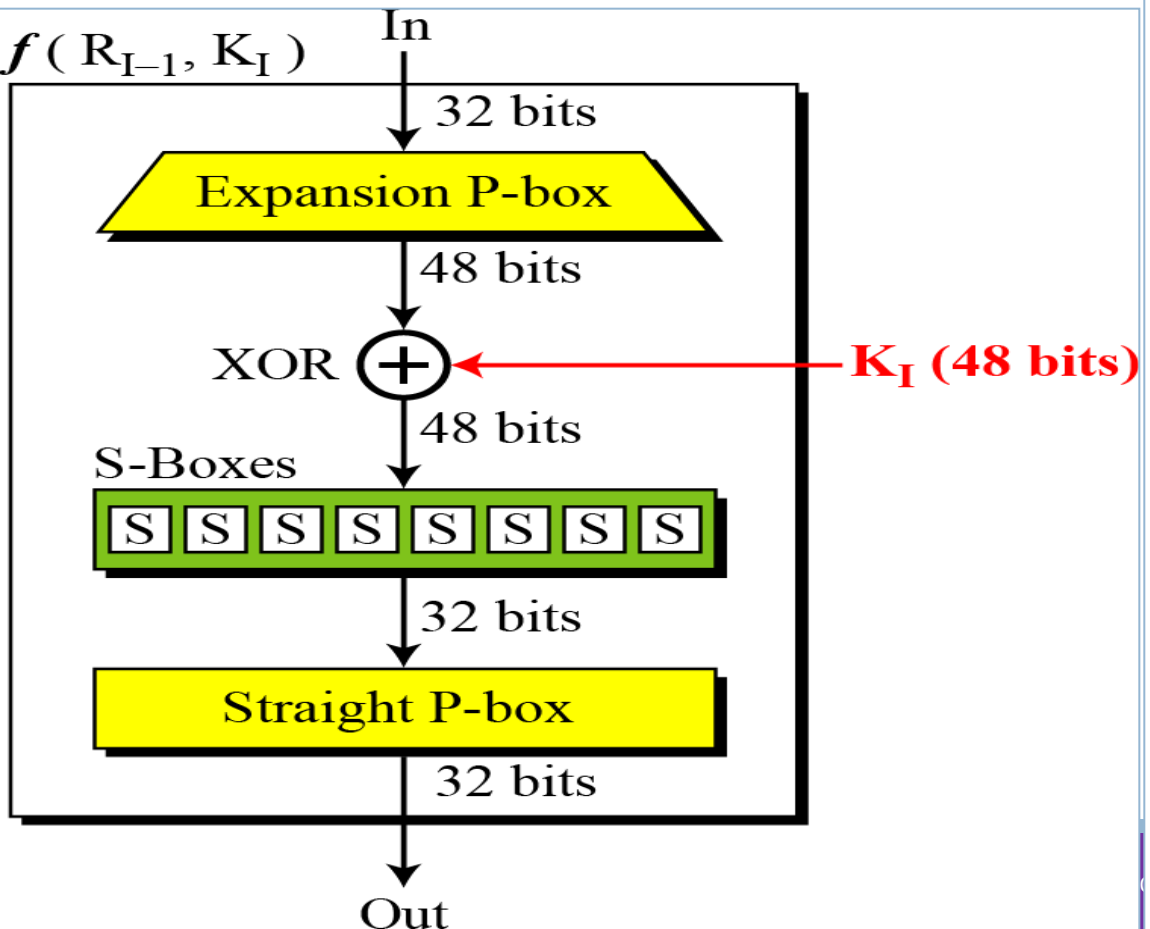
- The heart of this cipher is the DES **function *f***.
- The DES function applies a 48-bit key to the rightmost 32 bits to produce a 32-bit output.

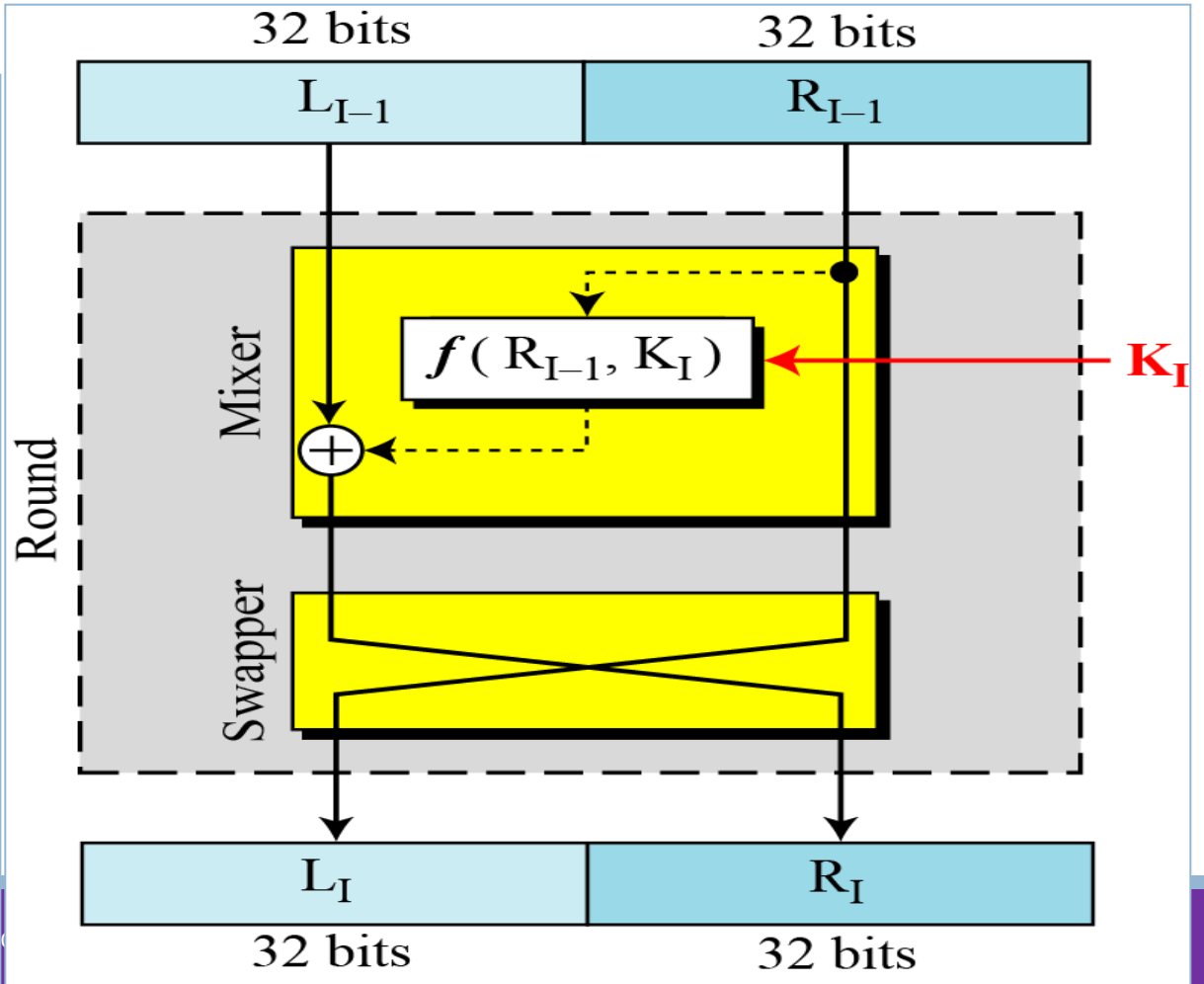


RAMAIAH
Institute of Technology

DES Structure

DES function

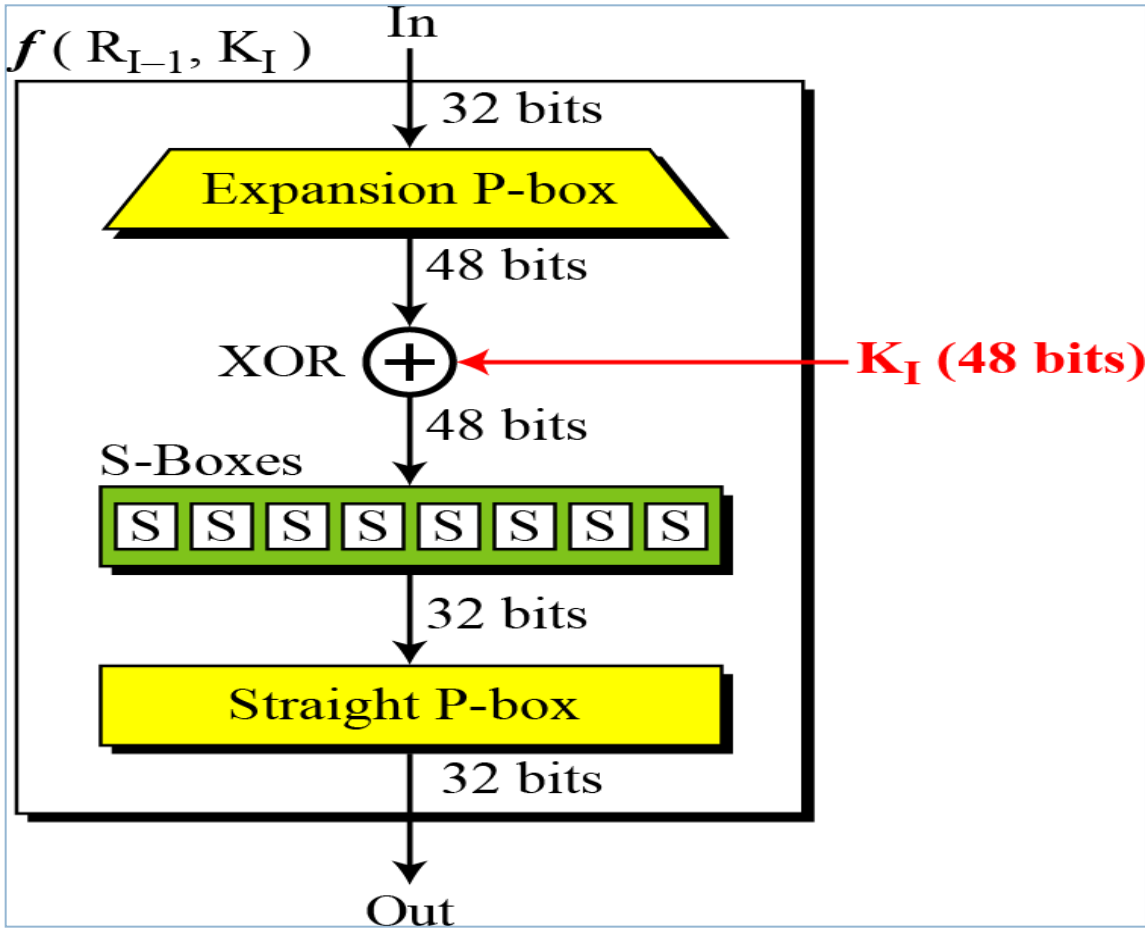




DES Structure

DES function

- Expansion P-Box
- Whitener (XOR)
- S-Boxes
- Straight P-Box

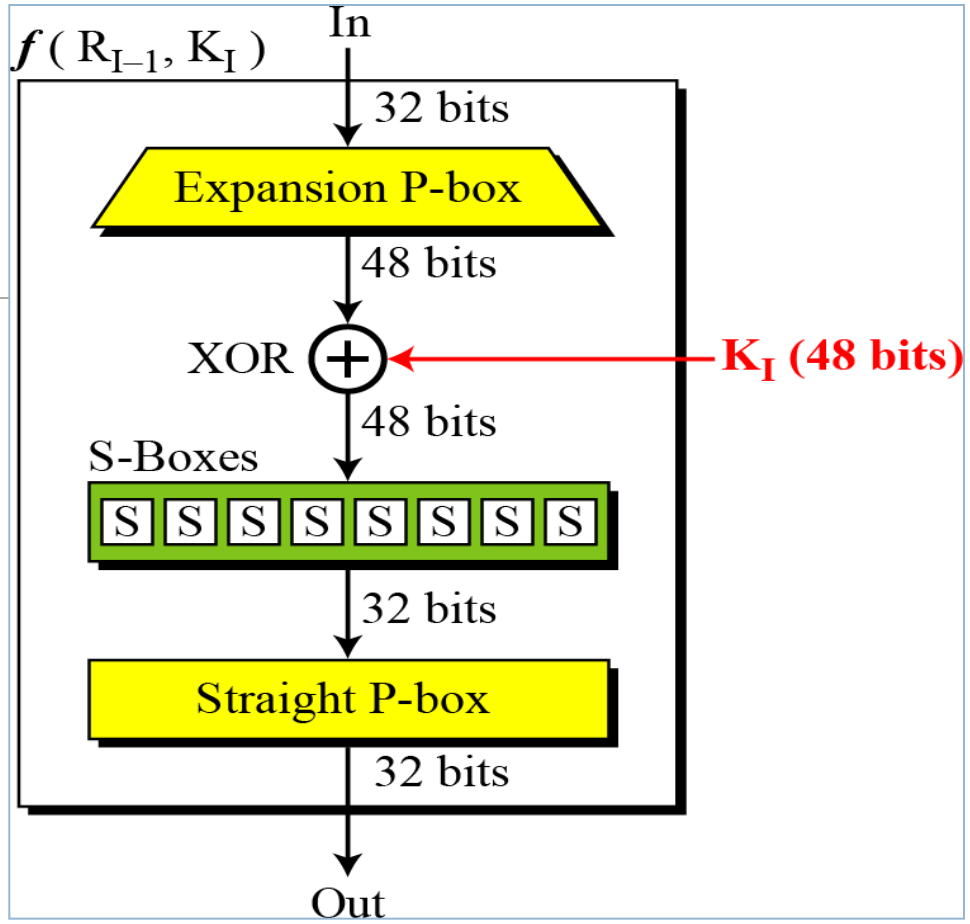


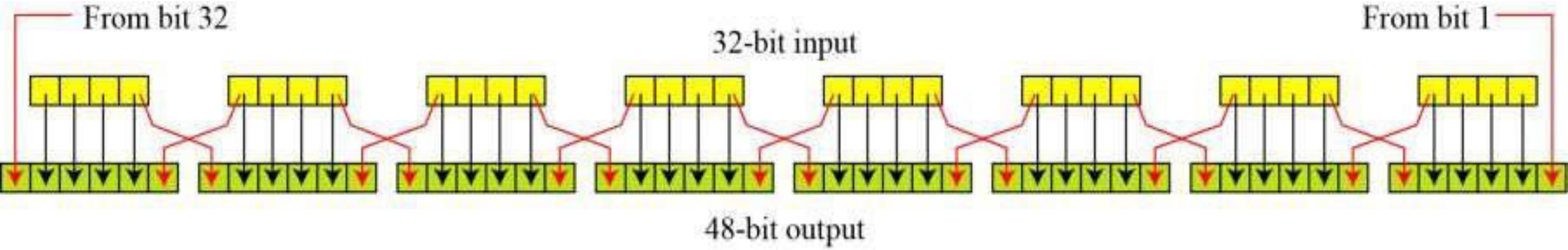
RAMAIAH Institute of Technology

DES Structure

DES function - Expansion P-Box

- RPT is expanded from 32 bits to 48 bits.
- Bits are permuted as well hence called expansion permutation.
- This happens as the 32-bit RPT is divided into 8 blocks, with each block consisting of 4 bits.
- Then, each 4-bit block of the previous step is then expanded to a corresponding 6-bit block, i.e., per 4-bit block, 2 more bits are added.





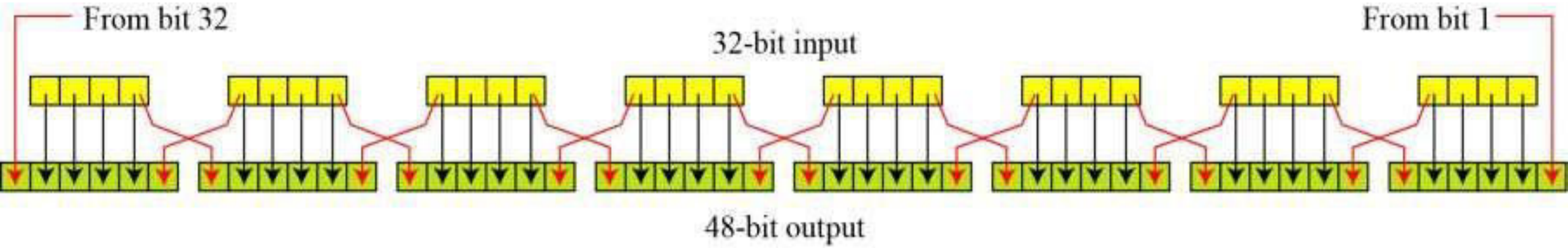
RAMAIAH
Institute of Technology

DES Structure

DES function - Expansion P-Box

- RPT is expanded from 32 bits to 48 bits.
- Bits are permuted as well hence called expansion permutation.
- This happens as the 32-bit RPT is divided into 8 blocks, with each block consisting of 4 bits.
- Then, each 4-bit block of the previous step is then expanded to a corresponding 6-bit block, i.e., per 4-bit block, 2 more bits are added.

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

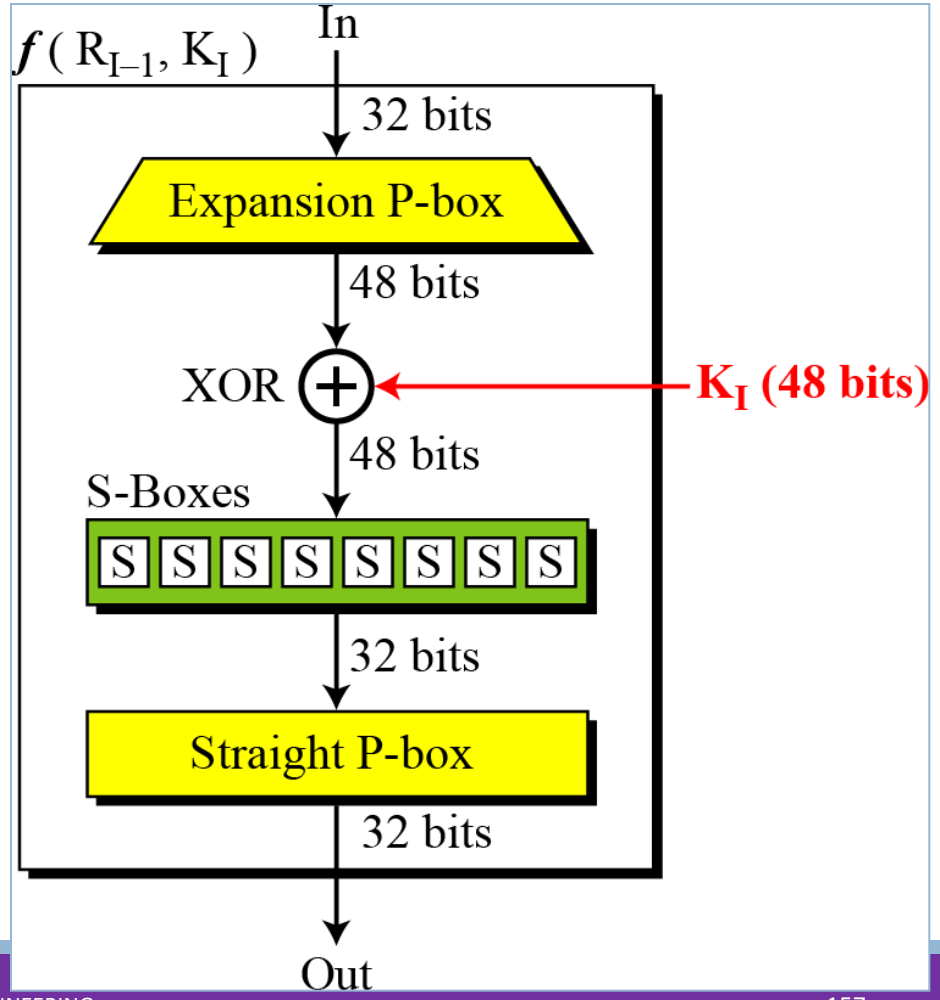


DES Structure

DES function - Whitener (XOR)

After the expansion permutation, DES does XOR operation on the expanded right section and the round key.

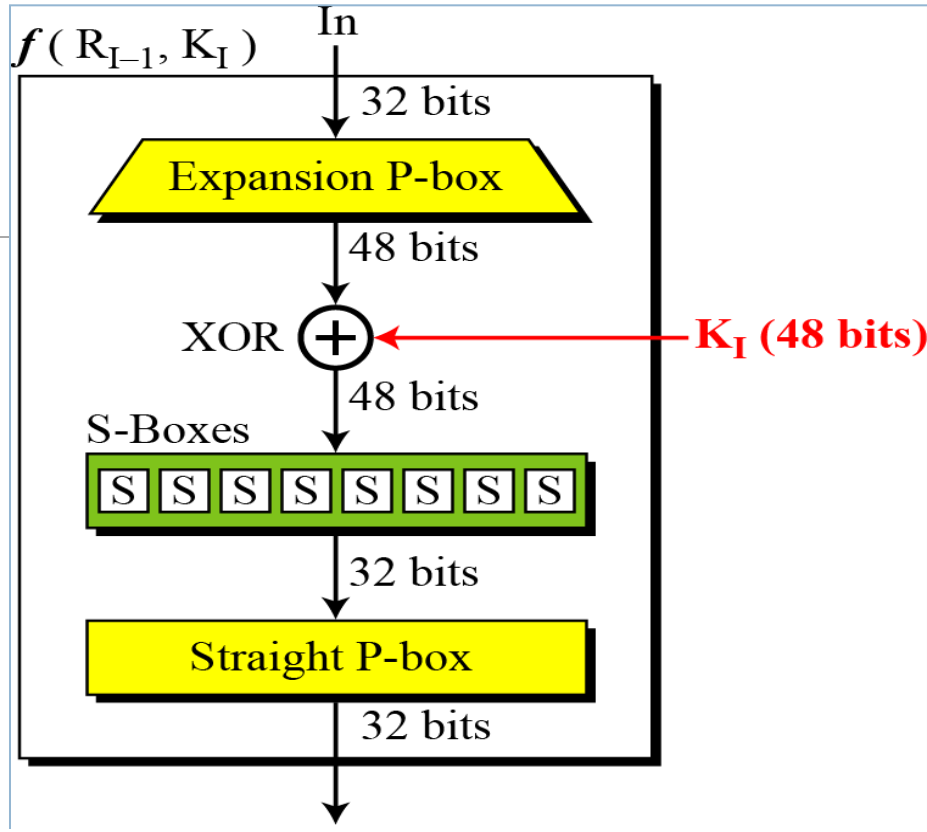
The round key is used only in this operation.

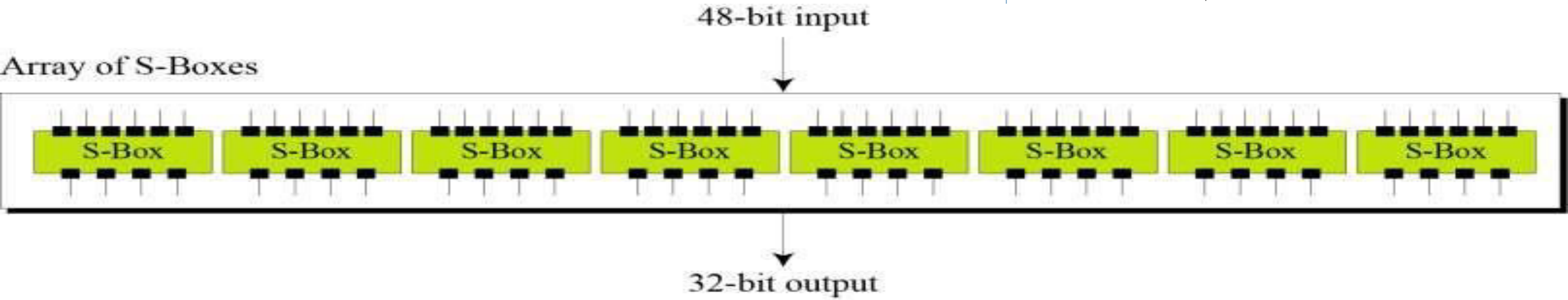


DES Structure

DES function - S-Boxes

- The S-boxes carry out the real mixing (confusion).
- DES uses 8 S-boxes, each with a 6-bit input and a 4-bit output.

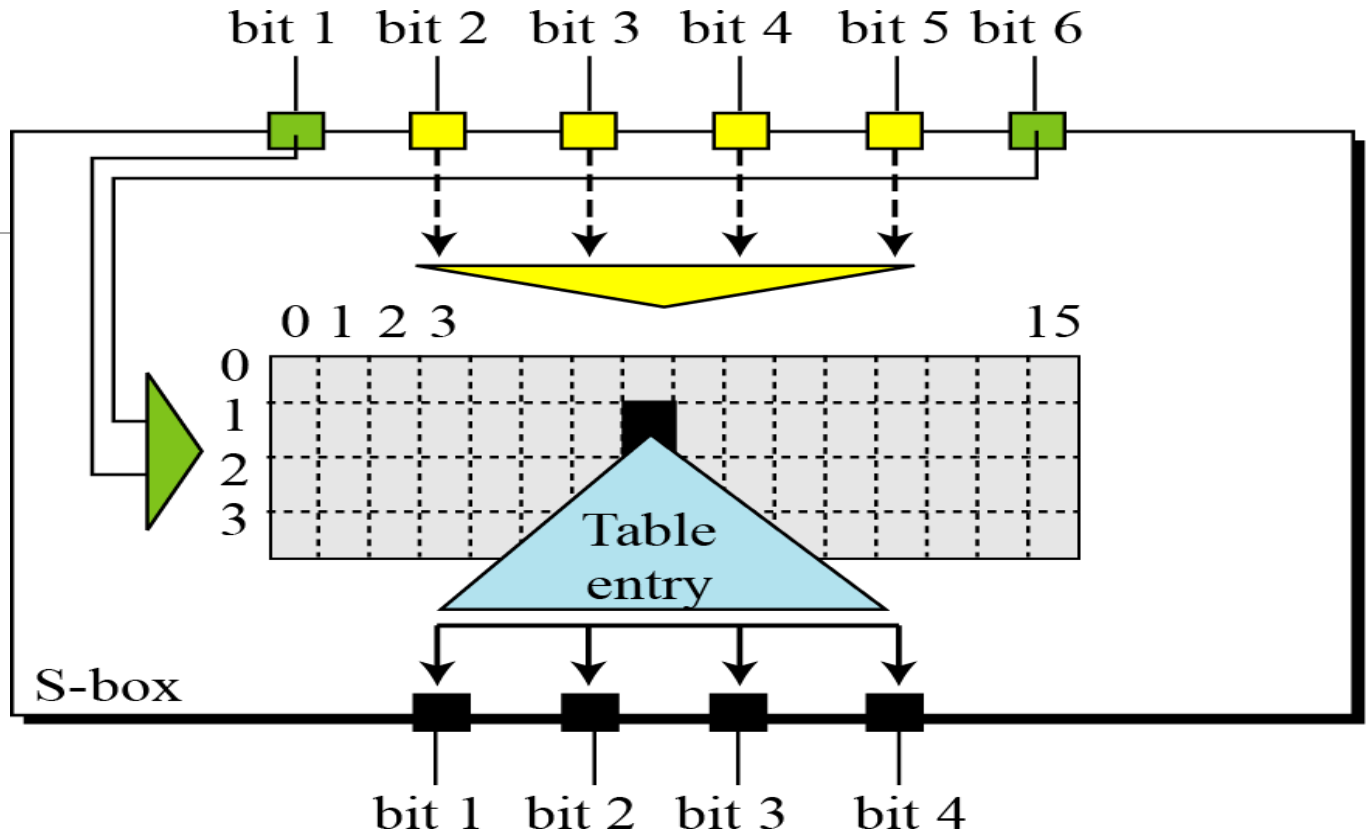


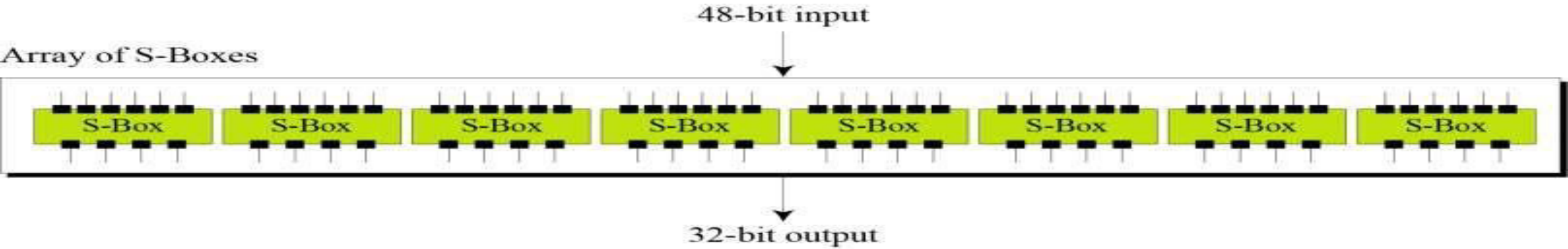


RAMAIAH
Institute of Technology

DES Structure

DES function - **S-Boxes**





DES Structure

DES function - S-Boxes

B = 011011 the first bit is "0" and the last bit "1" giving 01 as the row. This is row 1.

The middle four bits are "**1101**". This is the binary equivalent of decimal 13, so the column is column number 13.

In row 1, column 13 appears 5. This determines the output; 5 is binary 0101, so that the output is 0101.

Hence $\mathbf{S_1}(011011) = 0101$.

S-box 1

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0	14	04	13	01	02	15	11	08	03	10	06	12	05	09	00	07
1	00	15	07	04	14	02	13	10	03	06	12	11	09	05	03	08
2	04	01	14	08	13	06	02	11	15	12	09	07	03	10	05	00
3	15	12	08	02	04	09	01	07	05	11	03	14	10	00	06	13

DES Structure

DES function - S-Boxes

S-box 2

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0	15	01	08	14	06	11	03	04	09	07	02	13	12	00	05	10
1	03	13	04	07	15	02	08	14	12	00	01	10	06	09	11	05
2	00	14	07	11	10	04	13	01	05	08	12	06	09	03	02	15
3	13	08	10	01	03	15	04	02	11	06	07	12	00	05	14	09

S-box 3

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0	10	00	09	14	06	03	15	05	01	13	12	07	11	04	02	08
1	13	07	00	09	03	04	06	10	02	08	05	14	12	11	15	01
2	13	06	04	09	08	15	03	00	11	01	02	12	05	10	14	07
3	01	10	13	00	06	09	08	07	04	15	14	03	11	05	02	12

S-box 4

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0	07	13	14	03	00	6	09	10	1	02	08	05	11	12	04	15
1	13	08	11	05	06	15	00	03	04	07	02	12	01	10	14	09
2	10	06	09	00	12	11	07	13	15	01	03	14	05	02	08	04
3	03	15	00	06	10	01	13	08	09	04	05	11	12	07	02	14

DES Structure

DES function - S-Boxes

S-box 6

	0	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*
0	12	01	10	15	09	02	06	08	00	13	03	04	14	07	05	11
1	10	15	04	02	07	12	09	05	06	01	13	14	00	11	03	08
2	09	14	15	05	02	08	12	03	07	00	04	10	01	13	11	06
3	04	03	02	12	09	05	15	10	11	14	01	07	10	00	08	13

S-box 7

	0	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*
0	4	11	2	14	15	00	08	13	03	12	09	07	05	10	06	01
1	13	00	11	07	04	09	01	10	14	03	05	12	02	15	08	06
2	01	04	11	13	12	03	07	14	10	15	06	08	00	05	09	02
3	06	11	13	08	01	04	10	07	09	05	00	15	14	02	03	12

S-box 8

	0	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*
0	13	02	08	04	06	15	11	01	10	09	03	14	05	00	12	07
1	01	15	13	08	10	03	07	04	12	05	06	11	10	14	09	02
2	07	11	04	01	09	12	14	02	00	06	10	10	15	03	05	08
3	02	01	14	07	04	10	8	13	15	12	09	09	03	05	06	11

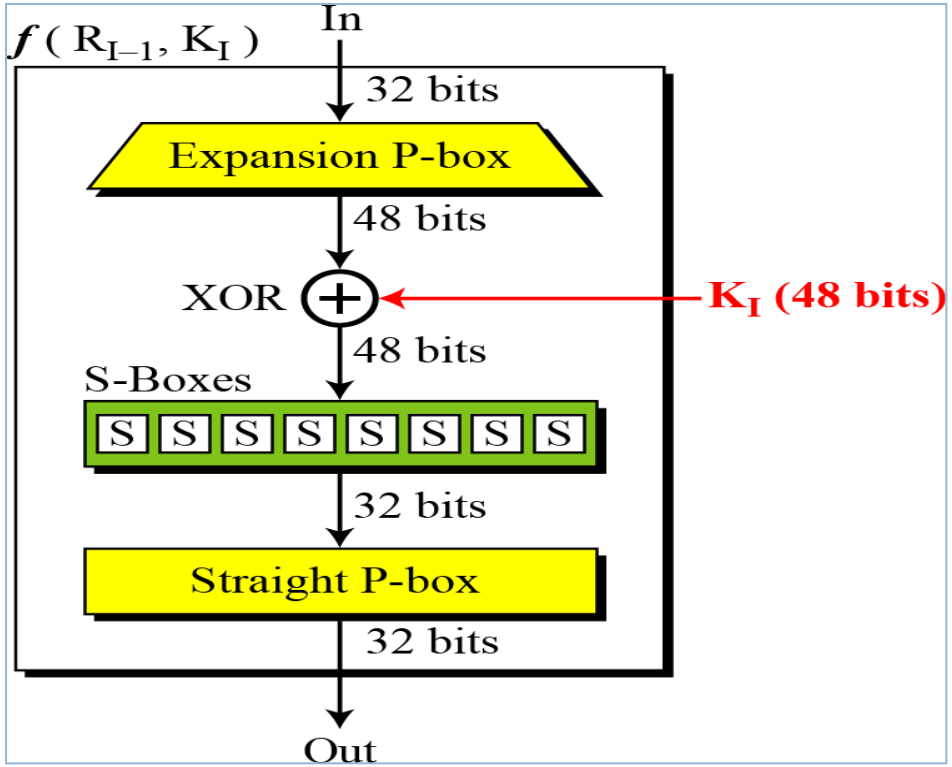
DES Structure

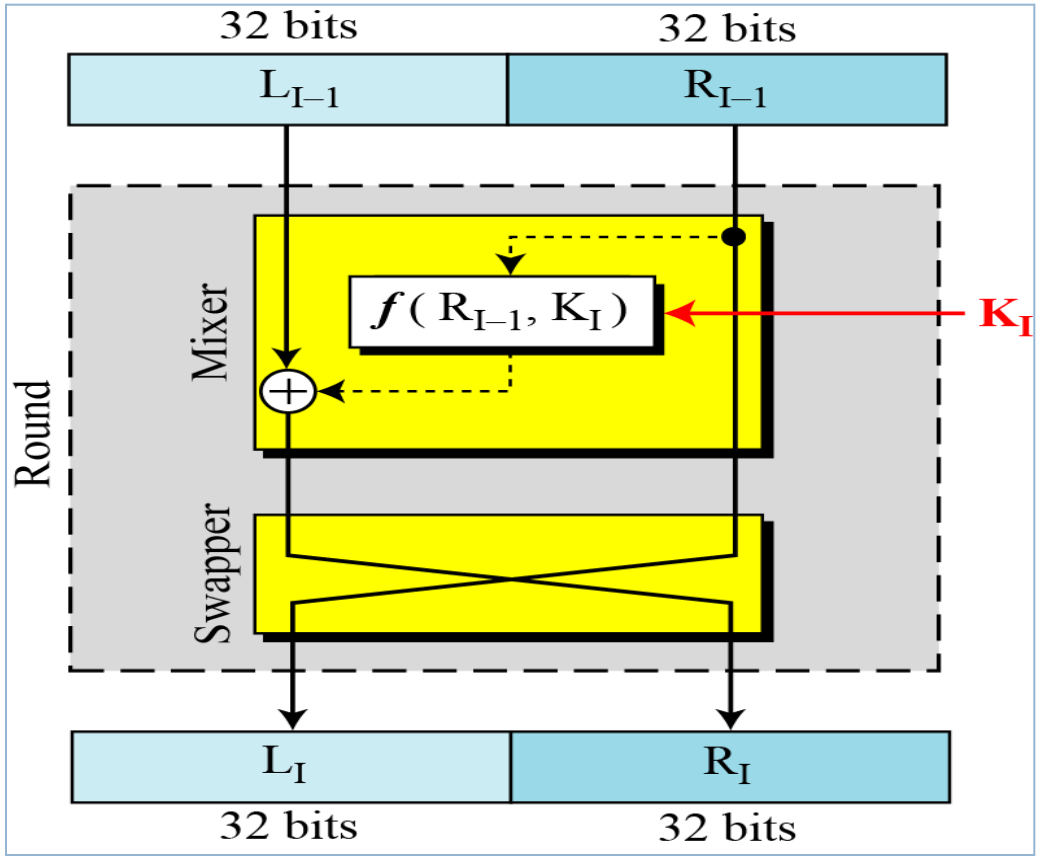
DES function - Straight P-Box

The 32 bit output of S-boxes is then subjected to the straight permutation with rule shown in the following illustration:

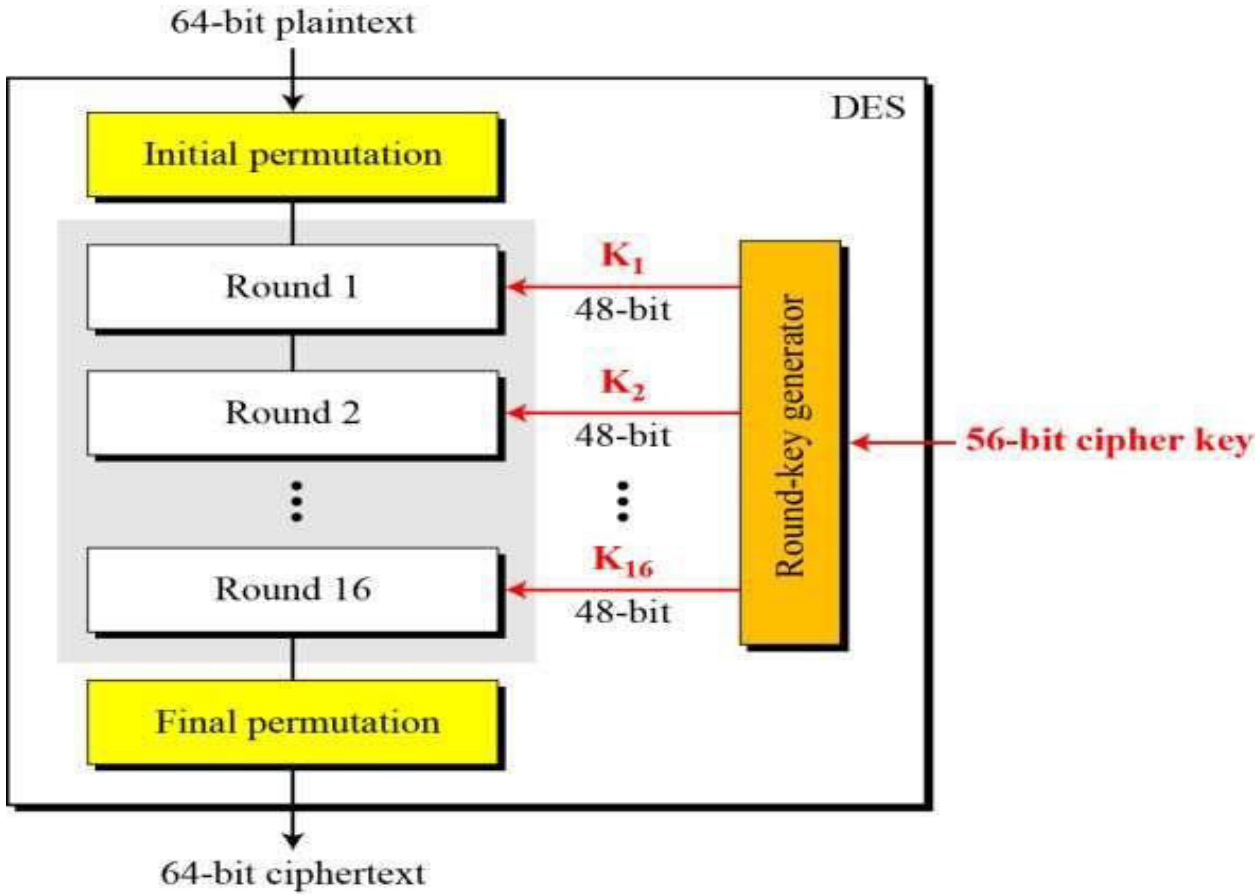
16	07	20	21	29	12	28	17
01	15	23	26	05	18	31	10
02	08	24	14	32	27	03	09
19	13	30	06	22	11	04	25

DES Structure



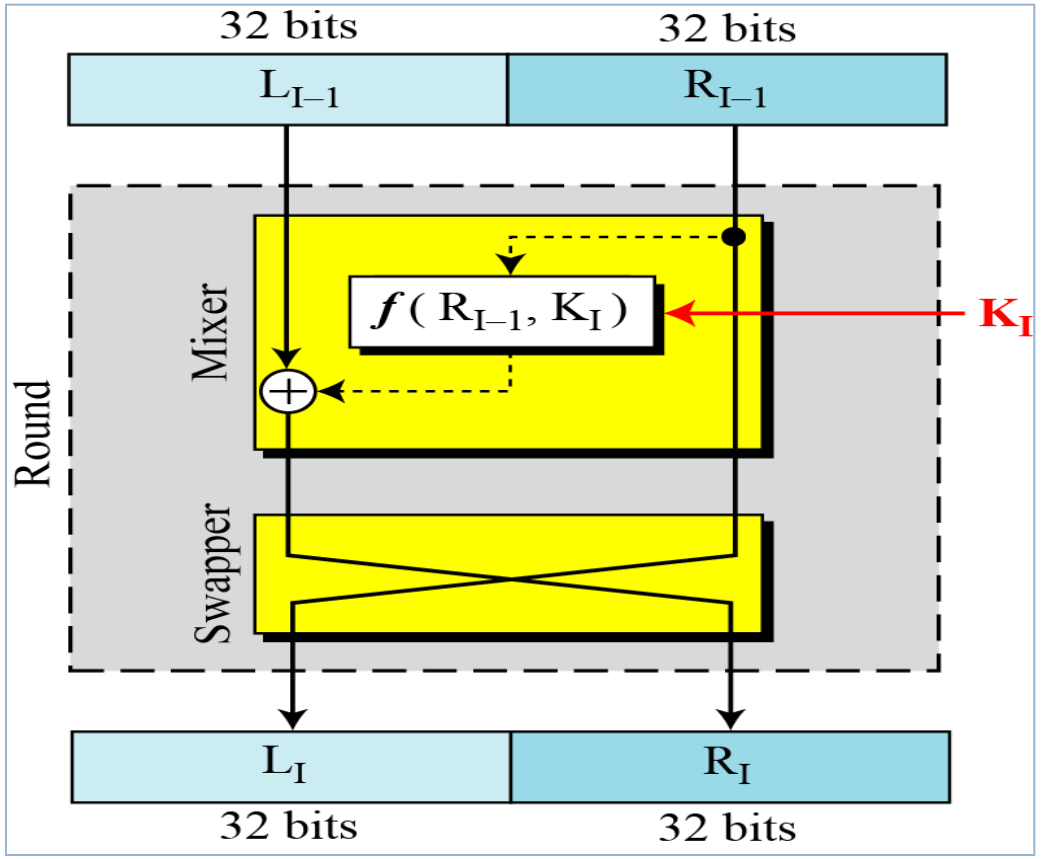


DES Structure



Cipher and Reverse Cipher

- Using Mixer and Swapper, we can create the cipher and reverse cipher, each having 16rounds.
- Cipher is used at encryption site
- Reverse cipher is used at decryption site
- Whole idea is to make cipher and reverse cipher similar

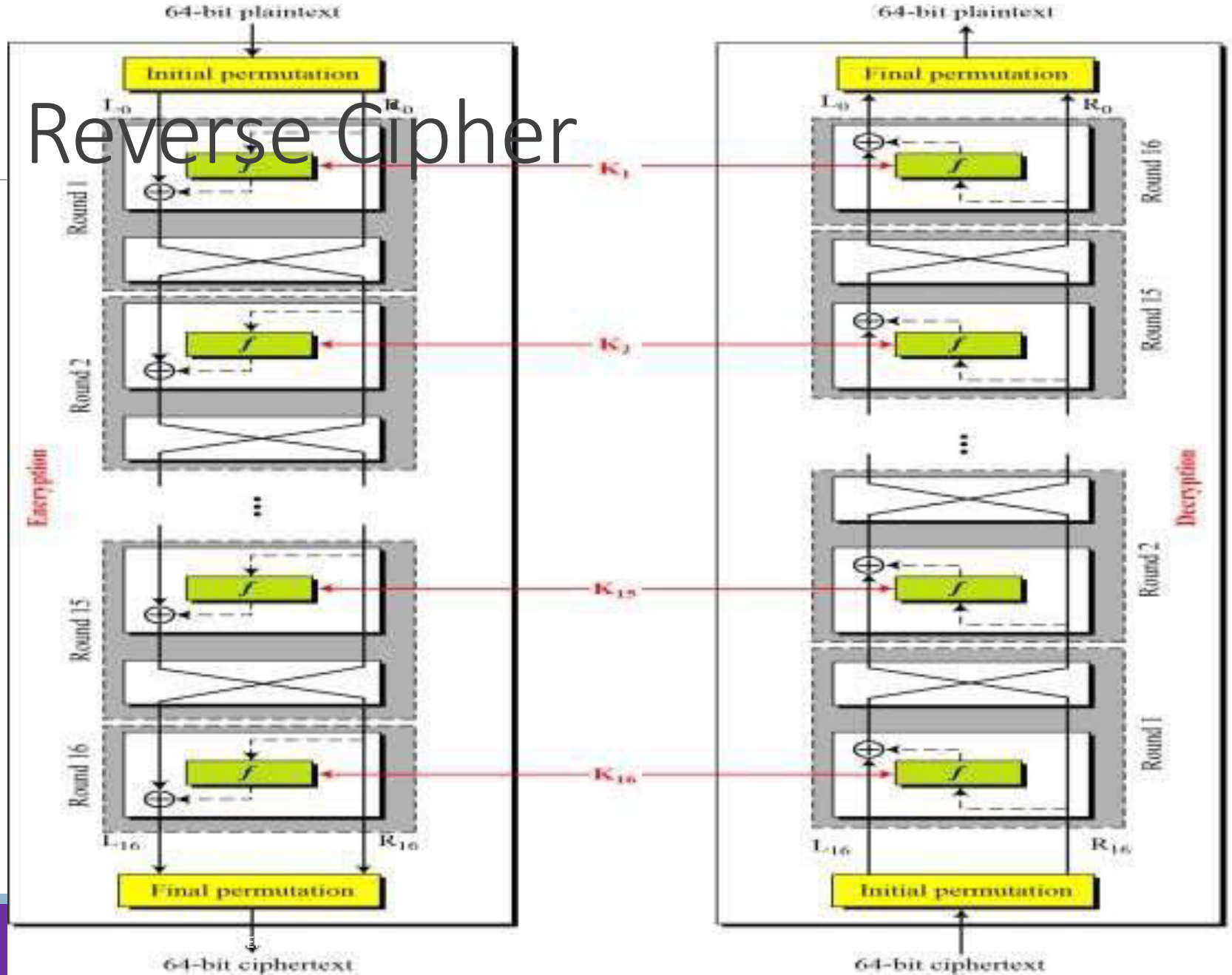


RAMAIAH Institute of Technology

Cipher and Reverse Cipher

First Approach

Make the last round (round 16) different from others, it has only mixer and no swapper



Pseudocode for cipher – First approach

```
Cipher (plainBlock[64], RoundKeys[16, 48], cipherBlock[64])
{
    permute (64, 64, plainBlock, inBlock, InitialPermutationTable)
    split (64, 32, inBlock, leftBlock, rightBlock)
    for (round = 1 to 16)
    {
        mixer (leftBlock, rightBlock, RoundKeys[round])
        if (round!=16) swapper (leftBlock, rightBlock)
    }
    combine (32, 64, leftBlock, rightBlock, outBlock)
    permute (64, 64, outBlock, cipherBlock, FinalPermutationTable)
}
```

Pseudocode for cipher – First approach

```
mixer (leftBlock[48], rightBlock[48], RoundKey[48])
{
    copy (32, rightBlock, T1)
    function (T1, RoundKey, T2)
    exclusiveOr (32, leftBlock, T2, T3)
    copy (32, T3, rightBlock)
}
swapper (leftBlock[32], rigthBlock[32])
{
    copy (32, leftBlock, T)
    copy (32, rightBlock, leftBlock)
    copy (32, T, rightBlock)
}
```

Pseudocode for cipher – First approach

```
function (inBlock[32], RoundKey[48], outBlock[32])
{
    permute (32, 48, inBlock, T1, ExpansionPermutationTable)
    exclusiveOr (48, T1, RoundKey, T2)
    substitute (T2, T3, SubstituteTables)
    permute (32, 32, T3, outBlock, StraightPermutationTable)
}
```

```
substitute (inBlock[32], outBlock[48], SubstitutionTables[8, 4, 16])
{
    for (i = 1 to 8)
    {
        row ← 2 × inBlock[i × 6 + 1] + inBlock [i × 6 + 6]
        col ← 8 × inBlock[i × 6 + 2] + 4 × inBlock[i × 6 + 3] +
              2 × inBlock[i × 6 + 4] + inBlock[i × 6 + 5]

        value = SubstitutionTables [i][row][col]

        outBlock[[i × 4 + 1] ← value / 8;        value ← value mod 8
        outBlock[[i × 4 + 2] ← value / 4;        value ← value mod 4
        outBlock[[i × 4 + 3] ← value / 2;        value ← value mod 2
        outBlock[[i × 4 + 4] ← value
    }
}
```

Cipher and Reverse Cipher

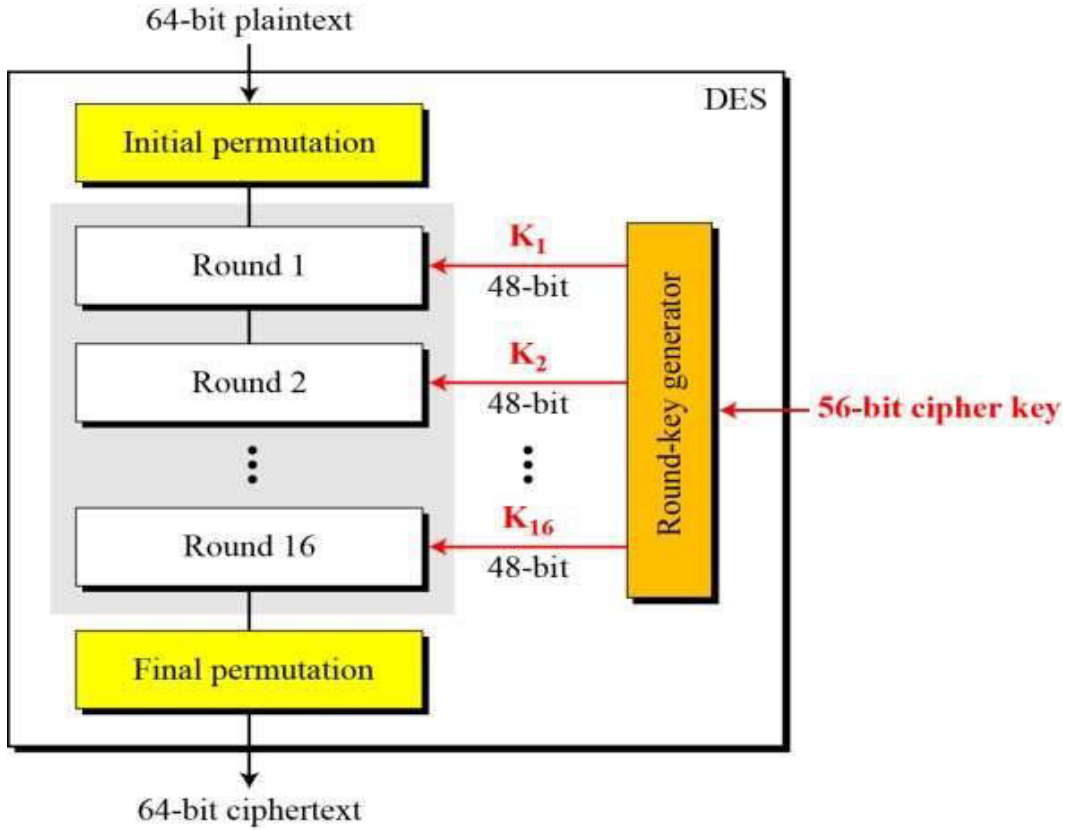
Alternative Approach

Make the all 16 rounds the same by including one swapper to the 16^{th} round and an extra swapper after that .

DES Structure

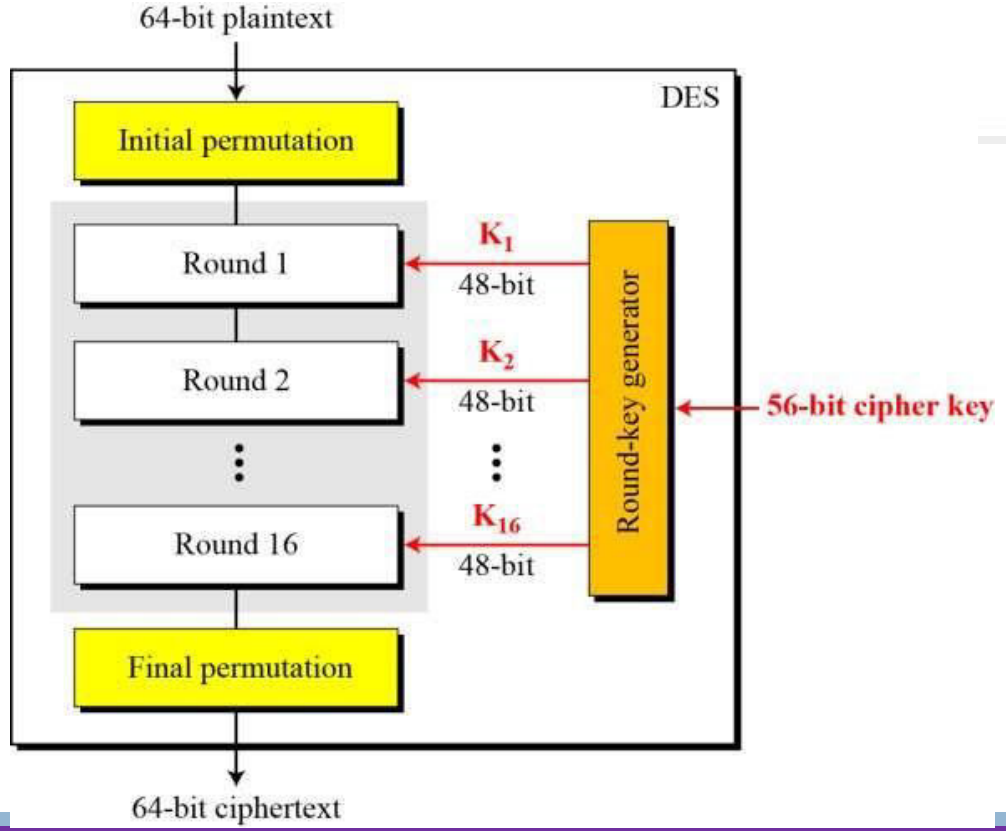
Round Key Generator

- The round-key generator creates sixteen 48-bit keys out of a 56-bit cipher key.
- The process of key generation is depicted in the following illustration



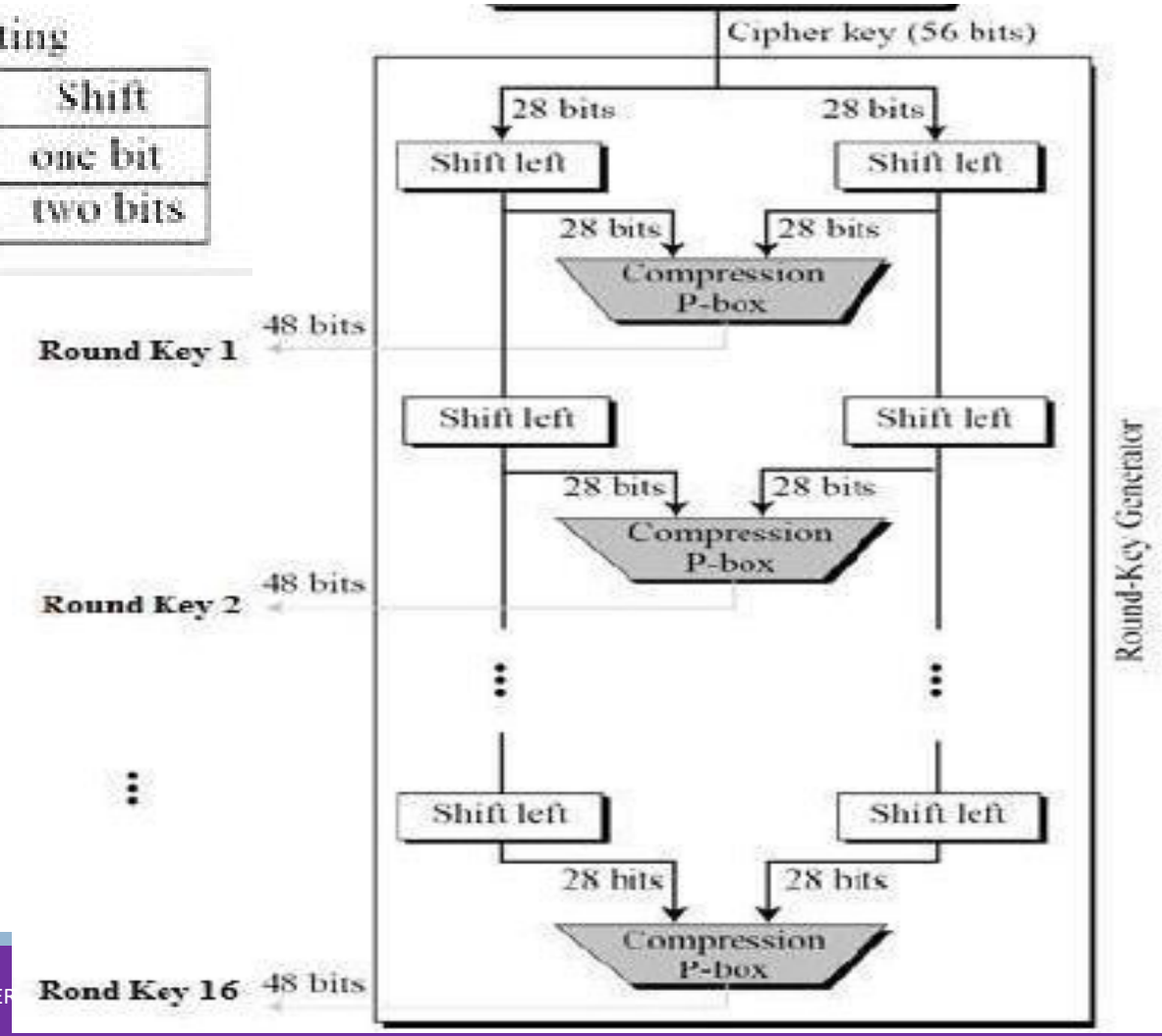
DES Structure

Round Key Generator



Shifting

Rounds	Shift
1, 2, 9, 16	one bit
Others	two bits



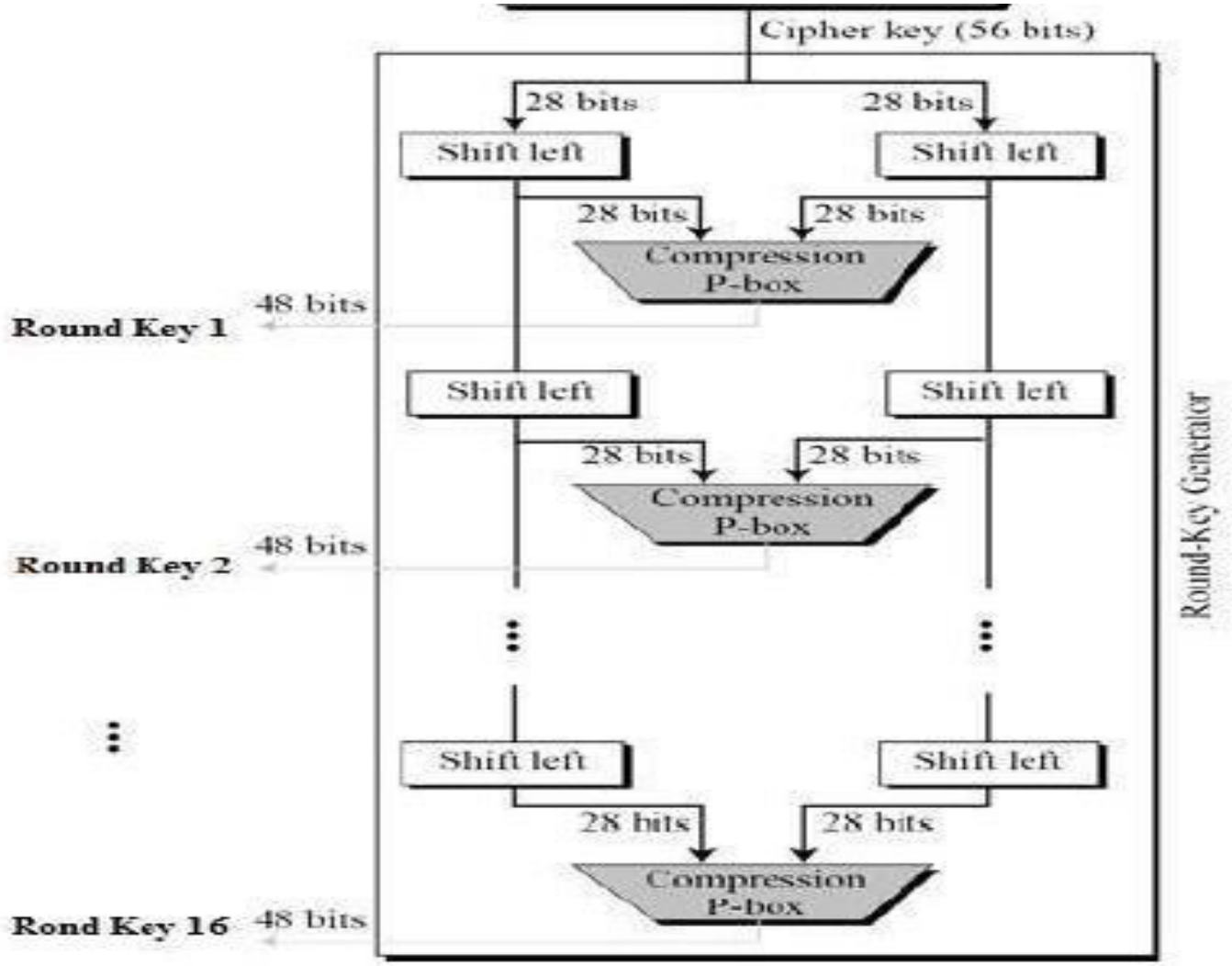
DES Structure

Round Key Generator

Shifting

Rounds	Shift
1, 2, 9, 16	one bit
Others	two bits

14	17	11	24	01	05	03	28
15	06	21	10	23	19	12	04
26	08	16	07	27	20	13	02
41	52	31	37	47	55	30	40
51	45	33	48	44	49	39	56
34	53	46	42	50	36	29	32



Round	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Bit shifts	1	1	2	2	2	2	2	2	1	2	2	2	2	2	2	1

DES Structure

Round Key Generator

```
Key_Generator (keyWithParities[64], RoundKeys[16, 48], ShiftTable[16])
{
    permute (64, 56, keyWithParities, cipherKey, ParityDropTable)
    split (56, 28, cipherKey, leftKey, rightKey)
     for (round = 1 to 16)
     {
          shiftLeft (leftKey, ShiftTable[round])
          shiftLeft (rightKey, ShiftTable[round])
          combine (28, 56, leftKey, rightKey, preRoundKey)
          permute (56, 48, preRoundKey, RoundKeys[round], KeyCompressionTable)
     }
}
```

DES Analysis

Properties of a Block Cipher

1. Avalanche Effect
2. Completeness Effect

Design Criteria

- S-Boxes
- P-Boxes
- Number of rounds

DES Weakness

1. Weakness in cipher design
   - S-Boxes
   - P-Boxes
2. Weakness in cipher key
   - Key size
   - Weak keys
   - Semi-weak keys
   - Possible Weak keys

DES Analysis

Properties of a Block Cipher - Avalanche Effect

- Avalanche effect is considered as one of the desirable property of any encryption algorithm.
- A slight change in either the key or the plain-text should result in a significant change in the cipher-text. This property is termed as avalanche effect.

DES Analysis

Properties of a Block Cipher - Avalanche Effect

Plaintext: 0000000000000000 Key: 22234512987ABB23
Ciphertext: 4789FD476E82A5F1

Plaintext: 0000000000000001 Key: 22234512987ABB23
Ciphertext: 0A4ED5C15A63FEA3

DES Analysis

Properties of a Block Cipher - Completeness Effect

Each bit of ciphertext depends on many bits of plaintext.

The diffusion and confusion produced by P-Box and S-Box in DES, shows strong completeness effect

DES Analysis

Design Criteria

- S-Boxes
- P-Boxes
- Number of rounds

DES Analysis

Design Criteria - S-Boxes

S-box 1

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0	14	04	13	01	02	15	11	08	03	10	06	12	05	09	00	07
1	00	15	07	04	14	02	13	10	03	06	12	11	09	05	03	08
2	04	01	14	08	13	06	02	11	15	12	09	07	03	10	05	00
3	15	12	08	02	04	09	01	07	05	11	03	14	10	00	06	13

- The entries of each row are permutations of values between 0 and 15.
- S-boxes are nonlinear.
- If we change a single bit in the input, two or more bits will be changed in the output.
- If two inputs to an S-box differ only in two middle bits (bits 3 and 4), the output must differ in at least two bits.
- If two inputs to an S-box differ in first two middle bits (bits 1 and 2) and the same in the last two bits (bits 5 and 6), the two outputs must different.

DES Analysis

Design Criteria - S-Boxes

6. There are only 32 6-bit input-word pairs (xi and xj), in which xi $\oplus$ xj $\neq (000000)_2$. These 32 input pairs create 32 4-bit output-word pairs. If we create the difference between the 32 output pairs, d = yi $\oplus$ yj, no more than 8 of these d's should be the same.

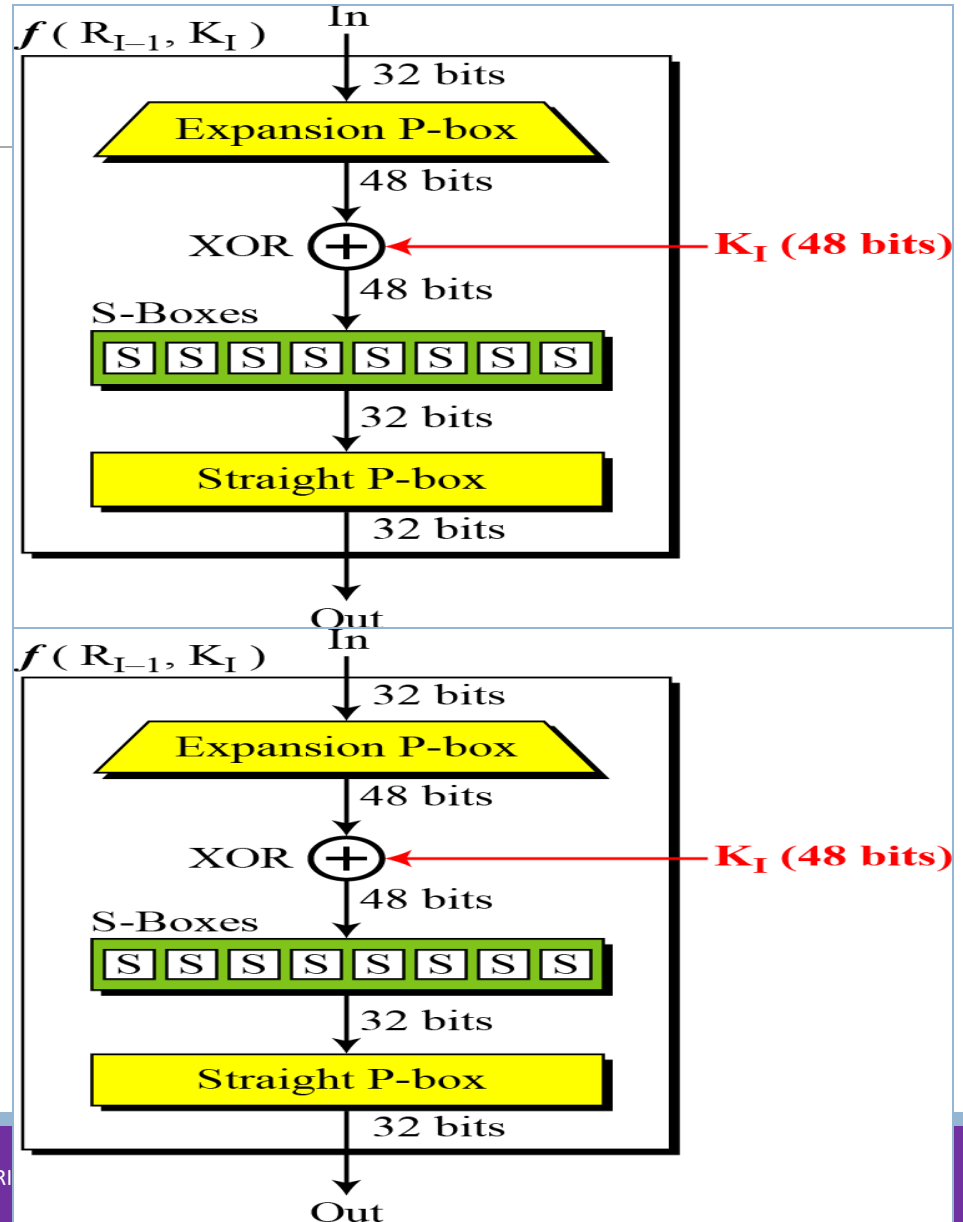
7. A criterion similar to #6 is applied to three S-boxes.

8. In any S-box, if a single input bit is held constant (0 or 1) and other bits are changed randomly, the differences between the numbers of 0s and 1s are minimized.

DES Analysis

Design Criteria - P-Boxes

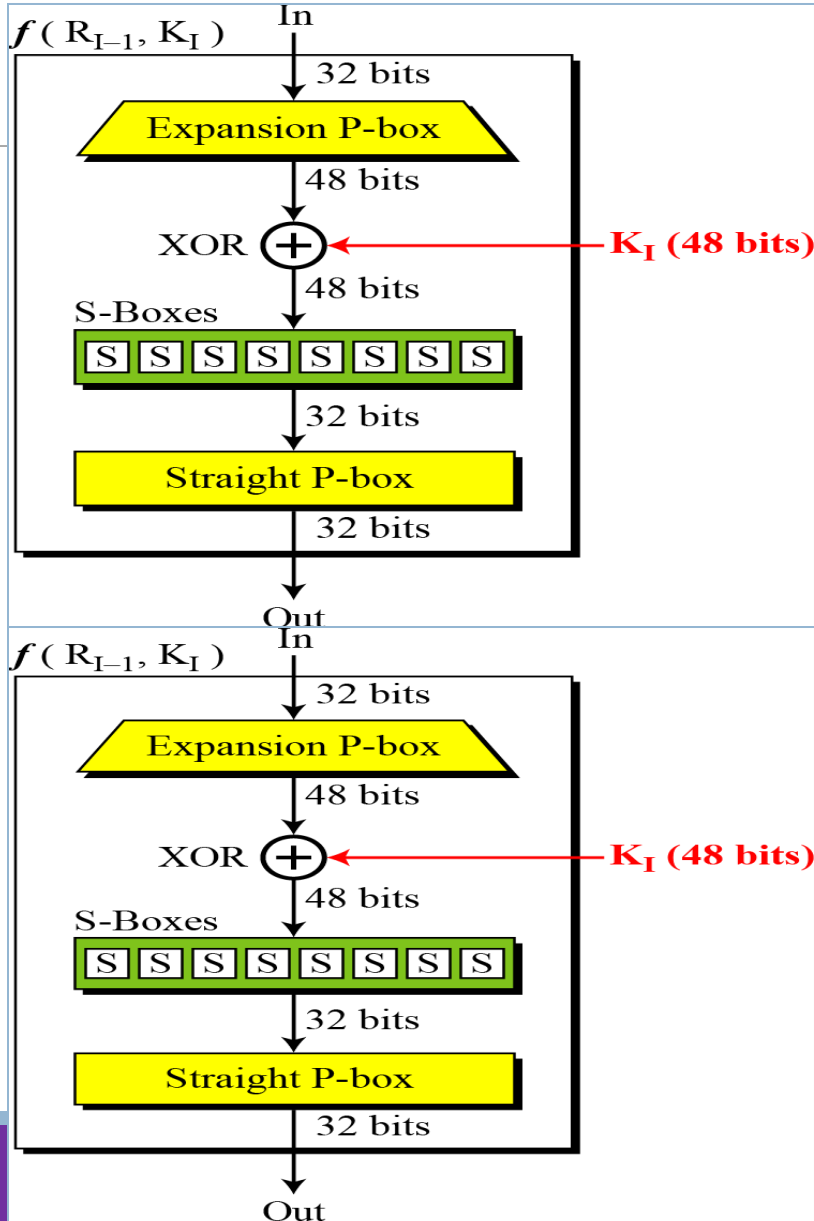
- Between two rows of S-boxes (in two subsequent rounds), there are one straight P-box and one expansion P-box.
- These two P-boxes provide diffusion of bits.



DES Analysis

Design Criteria - P-Boxes

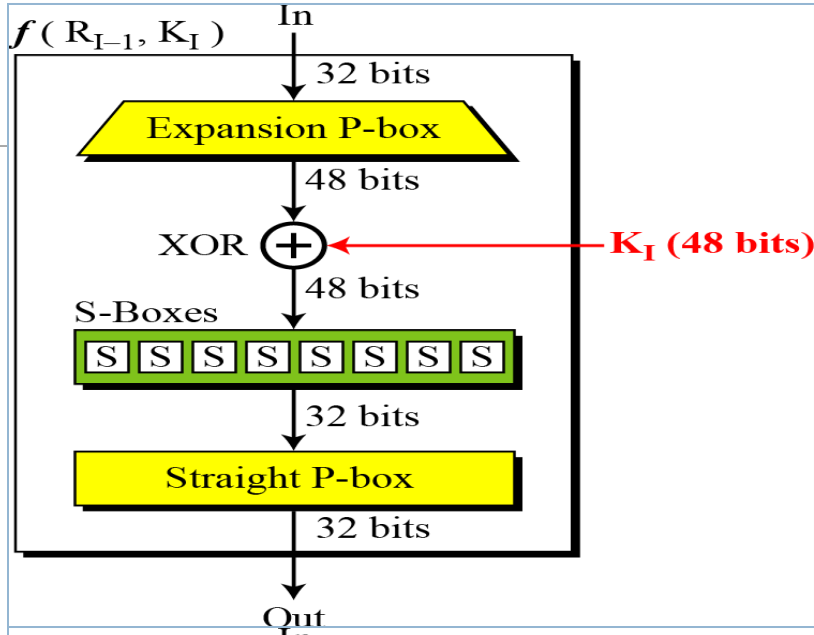
- Each S-box input comes from the output of a different S-box.
- No input to a given S-box comes from the output from the same box (in the previous round).
- The four outputs from each S-box go to six different S-boxes (in the next round).
- No two output bits from an S-box go to the same S-box (in the next round).

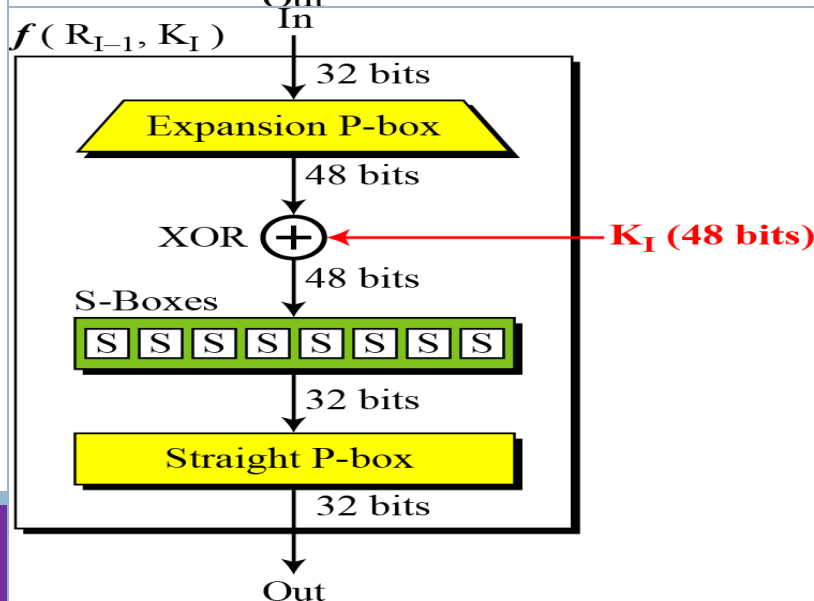


DES Analysis

Design Criteria - P-Boxes

- If we number the eight S-boxes, S1, S2, …, S8,
  - An output of S_{j-2} goes to one of the first two bits of Sj (in the next round).
  - An output of S_{j-1} goes to one of the last two bits of Sj (in the next round).
  - An output of S_{j+1} goes to one of the two middle bits of Sj (in the next round).

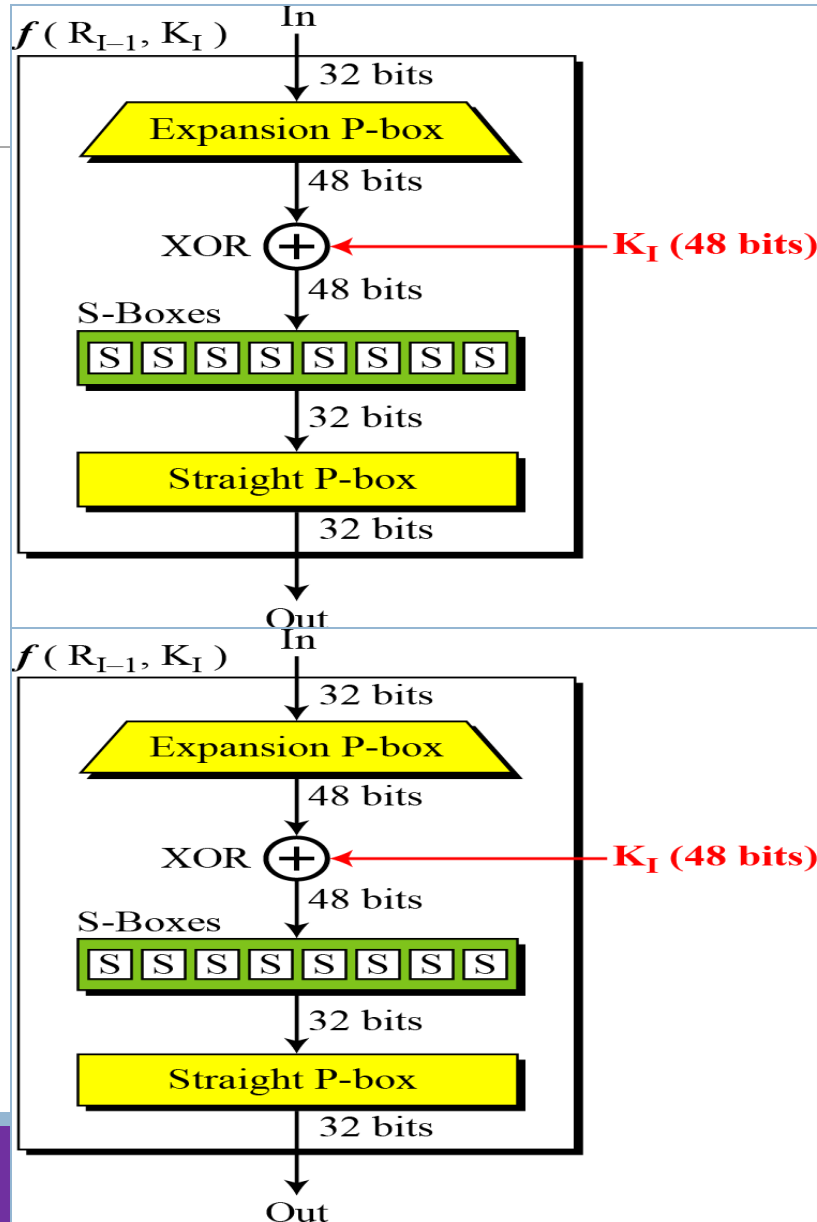




DES Analysis

Design Criteria - P-Boxes

- For each S-box, the two output bits go to the first or last two bits of an S-box in the next round. The other two output bits go to the middle bits of an S-box in the next round.
- If an output bit from Sj goes to one of the middle bits in Sk (in the next round), then an output bit from Sk cannot go to the middle bit of Sj. If we let j=k, this implies that none of the middle bits of an S-box can go to one of the middle bits of the same S-box the next round.



DES Analysis

Design Criteria - Number of rounds

- DES uses sixteen rounds of Feistel ciphers.
- It has been proved that after eight rounds, each ciphertext is a function of every plaintext bit and every key bit; the ciphertext is thoroughly a random function of plaintext and ciphertext.
- Therefore, it looks like 8 rounds should be enough.
- However, experiments have found that DES versions with less than 16 rounds are even more vulnerable to known-plaintext than brute-force attack, which justify the use of 16 rounds by the designers of DES.

DES Analysis

DES Weakness

1. Weakness in cipher design
   - S-Boxes
   - P-Boxes
2. Weakness in cipher key
   - Key size
   - Weak keys
   - Semi-weak keys
   - Possible weak keys

RAMAIAH Institute of Technology

DES Analysis

DES Weakness - Weakness in cipher design

S-Boxes

- In S-box 4, the last three output bits can be derived in the same way as the first output bit by complementing some of the input bits.
- Two specifically chosen inputs to an S-box array can create the same output.
- It is possible to obtain the same output in a single round by changing bits in only three neighboring S-boxes.

S-box 4

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0	07	13	14	03	00	6	09	10	1	02	08	05	11	12	04	15
1	13	08	11	05	06	15	00	03	04	07	02	12	01	10	14	09
2	10	06	09	00	12	11	07	13	15	01	03	14	05	02	08	04
3	03	15	00	06	10	01	13	08	09	04	05	11	12	07	02	14

DES Analysis

DES Weakness - Weakness in cipher design

P-Boxes

- It is not clear why designers of DES used the initial and final permutations; these have no security benefits.
- In the expansion permutation (inside the function), the first and fourth bits of every 4-bit series are repeated.

DES Analysis

DES Weakness - Weakness in cipher key

- Key size
- Weak keys
- Semi-weak keys
- Possible weak keys

DES Analysis

Weakness in cipher key - Key size(56 bits)

Brute force attack adversary will check with – 2^{56} keys

- One computer with processor → more than thousand years
- Computer with parallel processing → 20 hours
- Computer network with parallel processing → 120 days (key challenged by RSA Laboratories)

Solution :

3DES with two keys(112bits)

3DES with three keys(168 bits)

DES Analysis

Weakness in cipher key-Weak keys

- Four out of 2^{56} keys are called weak keys
- Round keys created from weak keys will have the same pattern as cipher key

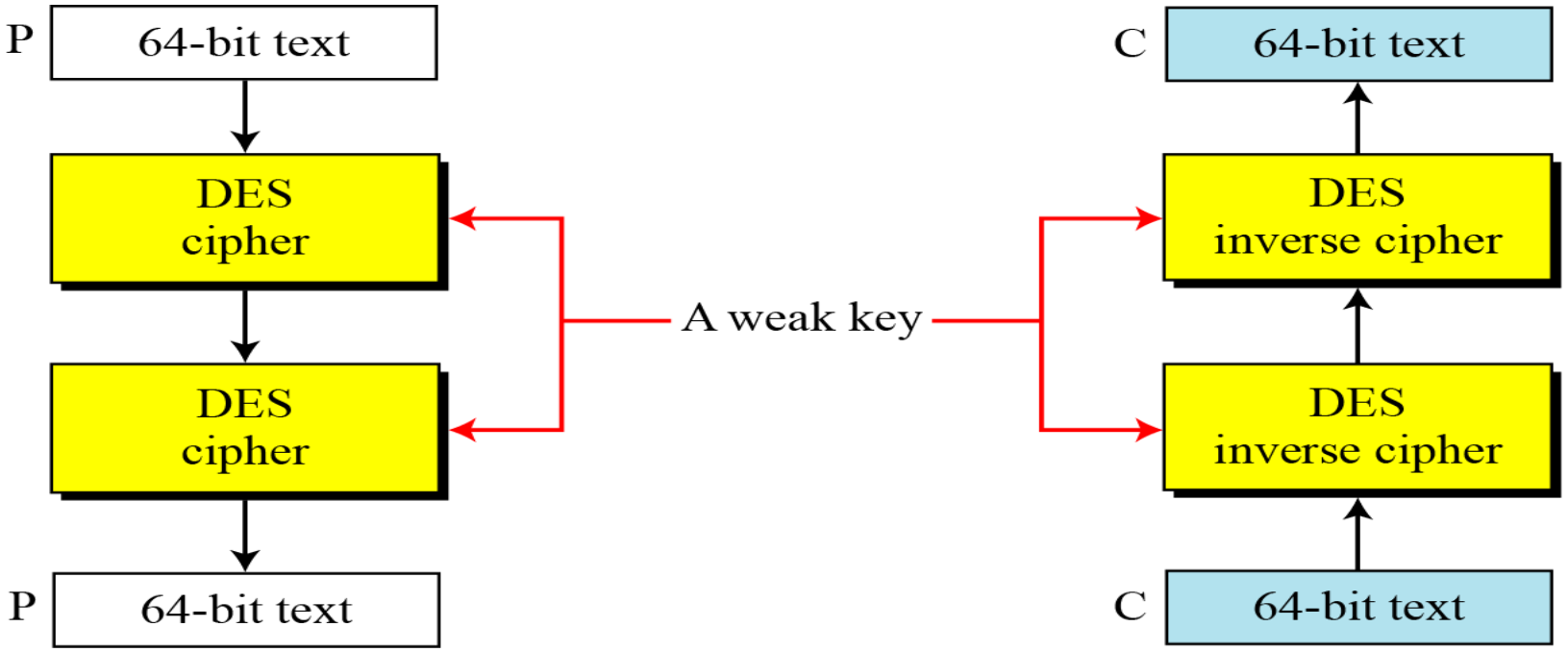
Table 6.18 *Weak keys*

Keys before parities drop (64 bits)	*Actual key (56 bits)*
0101 0101 0101 0101	0000000 0000000
1F1F 1F1F 0E0E 0E0E	0000000 FFFFFFF
E0E0 E0E0 F1F1 F1F1	FFFFFFF 0000000
FEFE FEFE FEFE FEFE	FFFFFFF FFFFFFF

DES Analysis

Weakness in cipher key-Weak keys

- What is the advantage of using weak keys



Double encryption and decryption with a weak key

DES Analysis

Table 6.18 *Weak keys*

Keys before parities drop (64 bits)	*Actual key (56 bits)*
0101 0101 0101 0101	0000000 0000000
1F1F 1F1F 0E0E 0E0E	0000000 FFFFFFF
E0E0 E0E0 F1F1 F1F1	FFFFFFF 0000000
FEFE FEFE FEFE FEFE	FFFFFFF FFFFFFF

Weakness in cipher key-Weak keys

Let us try the first weak key in Table 6.18 to encrypt a block two times.

After two encryptions with the same key the original plaintext block is created. Note that we have used the encryption algorithm two times, not one encryption followed by another decryption.

Key: 0x0101010101010101
Plaintext: *0x1234567887654321* ⟶ Ciphertext: 0x814FE938589154F7

Key: 0x0101010101010101
Plaintext: 0x814FE938589154F7 ⟶ Ciphertext: *0x1234567887654321*

$$E_k(E_k(P)) = P$$

RAMAIAH Institute of Technology

DES Analysis

Weakness in cipher key - Semi-weak keys

- There are six key pairs called semi weak keys
- A Semi weak keys creates two different round keys and each of them is repeated eight times
- Round key created from each pair are the same with different order

First key in the pair	*Second key in the pair*
01FE 01FE 01FE 01FE	FE01 FE01 FE01 FE01
1FE0 1FE0 0EF1 0EF1	E01F E01F F10E F10E
01E0 01E1 01F1 01F1	E001 E001 F101 F101
1FFE 1FFE 0EFE 0EFE	FE1F FE1F FE0E FE0E
011F 011F 010E 010E	1F01 1F01 0E01 0E01
E0FE E0FE F1FE F1FE	FEE0 FEE0 FEF1 FEF1

RAMAIAH Institute of Technology

DES Analysis

Weakness in cipher key - Semi-weak keys

First key in the pair	*Second key in the pair*
01FE 01FE 01FE 01FE	FE01 FE01 FE01 FE01

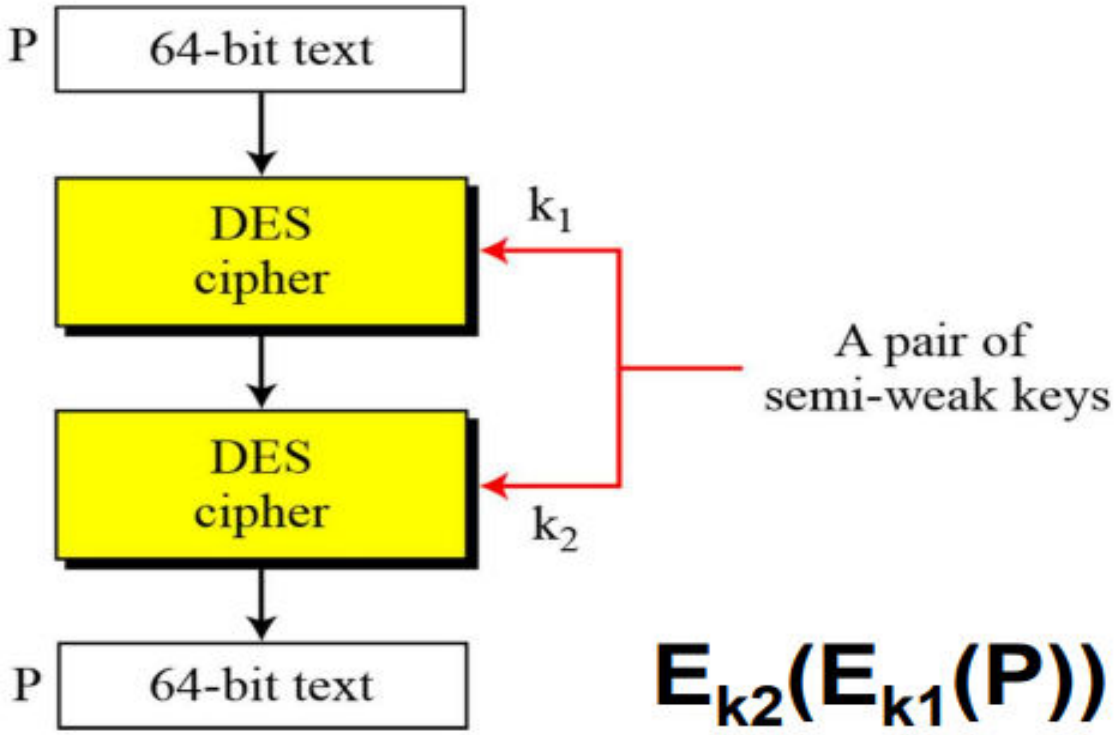
Round key 1	9153E54319BD	6EAC1ABCE642
Round key 2	6EAC1ABCE642	9153E54319BD
Round key 3	6EAC1ABCE642	9153E54319BD
Round key 4	6EAC1ABCE642	9153E54319BD
Round key 5	6EAC1ABCE642	9153E54319BD
Round key 6	6EAC1ABCE642	9153E54319BD
Round key 7	6EAC1ABCE642	9153E54319BD
Round key 8	6EAC1ABCE642	9153E54319BD
Round key 9	9153E54319BD	6EAC1ABCE642
Round key 10	9153E54319BD	6EAC1ABCE642
Round key 11	9153E54319BD	6EAC1ABCE642
Round key 12	9153E54319BD	6EAC1ABCE642
Round key 13	9153E54319BD	6EAC1ABCE642
Round key 14	9153E54319BD	6EAC1ABCE642
Round key 15	9153E54319BD	6EAC1ABCE642
Round key 16	6EAC1ABCE642	9153E54319BD

First key in the pair	*Second key in the pair*
01FE 01FE 01FE 01FE	FE01 FE01 FE01 FE01
1FE0 1FE0 0EF1 0EF1	E01F E01F F10E F10E
01E0 01E1 01F1 01F1	E001 E001 F101 F101
1FFE 1FFE 0EFE 0EFE	FE1F FE1F FE0E FE0E
011F 011F 010E 010E	1F01 1F01 0E01 0E01
E0FE E0FE F1FE F1FE	FEE0 FEE0 FEF1 FEF1

DES Analysis

Weakness in cipher key - Semi-weak keys

A pair of semi-weak keys in encryption and decryption



$$E_{k2}(E_{k1}(P)) = P$$

DES Analysis

Weakness in cipher key – Possible weak keys

- 48 Keys are possible weak keys
- A possible weak key is a key that creates four distinct round keys
- 16round keys = 4 groups → each group 4 equal round key

DES Analysis

Weakness in cipher key – Key clustering

- 2 or more different keys can create same ciphertext from the same plaintext.

Security of DES

DES, as the first important block cipher, has gone through much scrutiny.

Among the attempted attacks, three are of interest

- Brute Force attack
- Differential cryptanalysis
- Linear cryptanalysis

Security of DES

Brute Force attack

- DES can be broken using 2^{56}

Cryptanalysis is the process of transforming or decoding communications from non-readable to readable format without having access to the real key.

Different Forms of Cryptanalysis:

1. Differential Cryptanalysis:The use of differential cryptanalysis is to get clues about some critical bits, reducing the need for an extensive search.
2. Linear Cryptanalysis:The use of linear cryptanalysis is to figure out what is the linear relationship present between some plaintext bits, ciphertext bits, and unknown key bits very easily.

Security of DES

Differential cryptanalysis

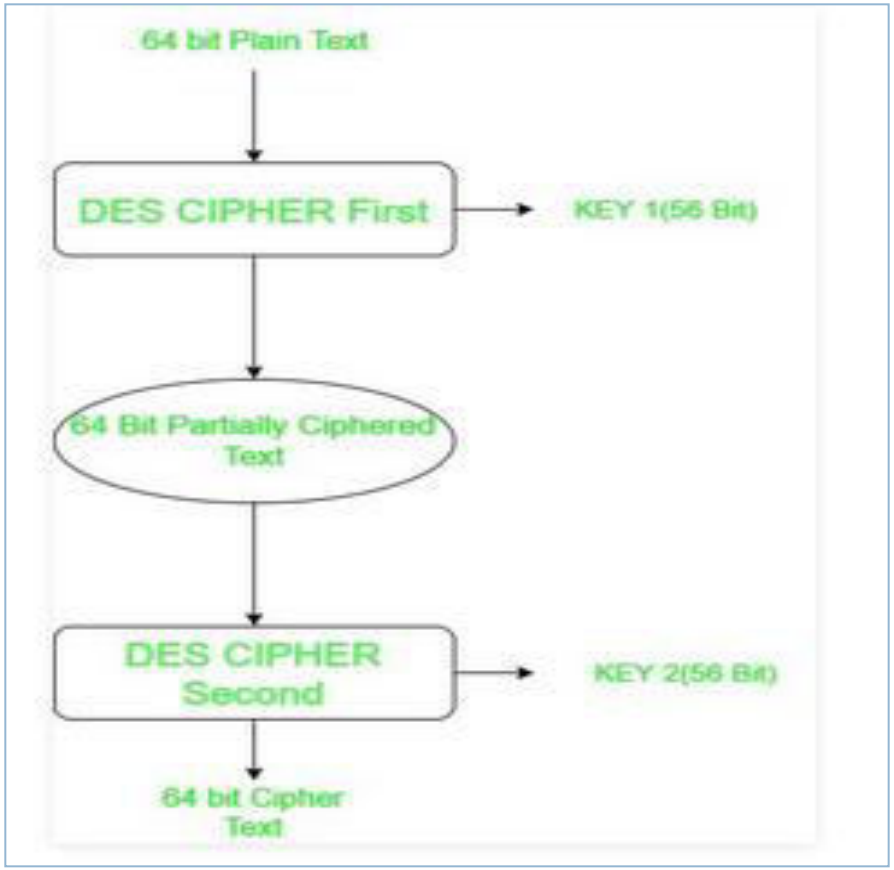
- It has been revealed that the designers of DES already knew about this type of attack and designed S-boxes and chose 16 as the number of rounds to make DES specifically resistant to this type of attack.

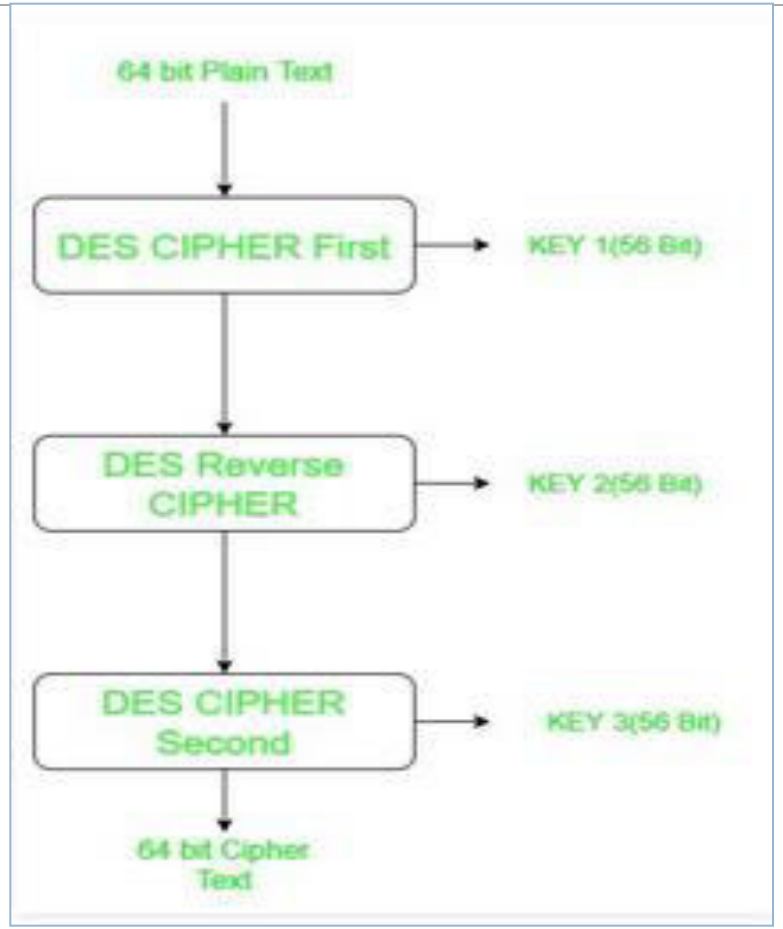
Security of DES

Linear cryptanalysis

- DES is more vulnerable to linear cryptanalysis than to differential cryptanalysis.
- S-boxes are not very resistant to linear cryptanalysis.
- DES can be broken using 2^{43} pairs of known plaintexts. However, from the practical point of view, finding so many pairs is very unlikely.

Double DES and Triple DES





RAMAIAH
Institute of Technology

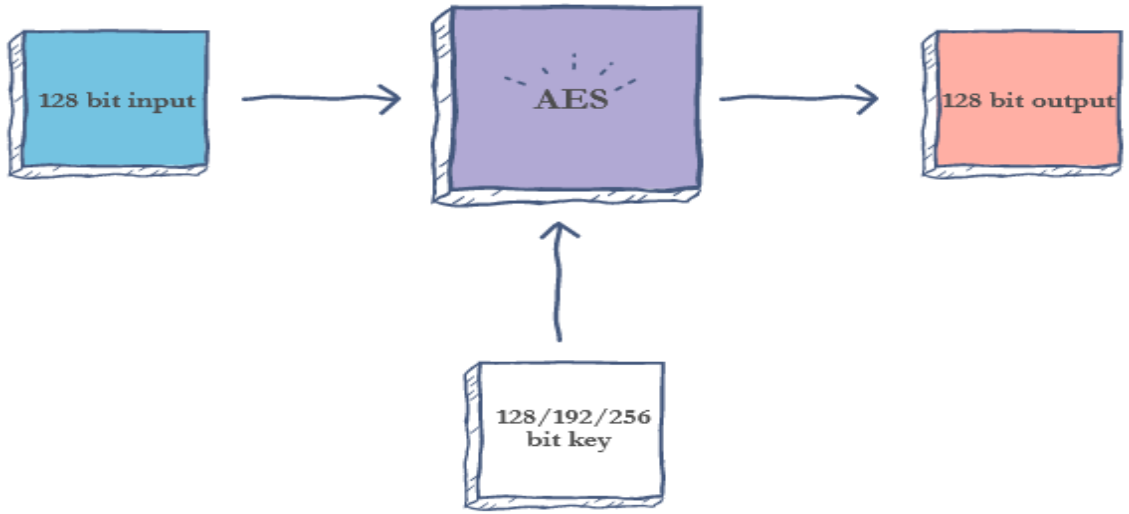
Why Was the AES Encryption Algorithm necessary?

Chronology of DES Cracking	
Broken for the first time	1997
Broken in 56 hours	1998
Broken in 22 hours and 15 minutes	1999
Capable of broken in 5 minutes	2021

Introduction

Advanced Encryption Standard (AES) features are as follows:

- Symmetric key symmetric block cipher
- 128-bit block data, 128/192/256-bit keys
- Stronger and faster than Triple-DES



	DES	AES
Developed	1977	2000
Cipher Type	Symmetric block cipher	Symmetric block cipher
Block size	64 bits	128 bits
Key length	56 bits	128/192/256 bits
Security	Rendered insecure	Considered secure

Introduction

- AES is an iterative rather than Feistel cipher.
- It is based on 'substitution–permutation network'.
- It comprises of a series of linked operations, some of which involve replacing inputs by specific outputs (substitutions) and others involve shuffling bits around (permutations).
- AES performs all its computations on bytes rather than bits.

Introduction

The Advanced Encryption Standard (AES) published by the National Institute of Standards and Technology (NIST) in December 2001.

- History
- Criteria
- Rounds
- Data Units
- Structure of Each Round

Introduction

History

- In February 2001, NIST announced that a draft of the Federal Information Processing Standard (FIPS) was available for public review and comment.
- Finally, AES was published as FIPS 197 in the Federal Register in December 2001.

Introduction

Criteria

The criteria defined by NIST for selecting AES fall into three areas:

1. Security -128bit key
2. Cost-Computational efficiency and storage requirements
3. Implementation -Flexibility(platform independent)

Introduction

Rounds

- AES is a non Feistel cipher that encrypts and decrypts a block of 128bit data.
- It uses 10,12 or 14 rounds → keysize-128/192/256bits

Introduction

Rounds

AES-128

AES-192

AES-256

But roundkey is

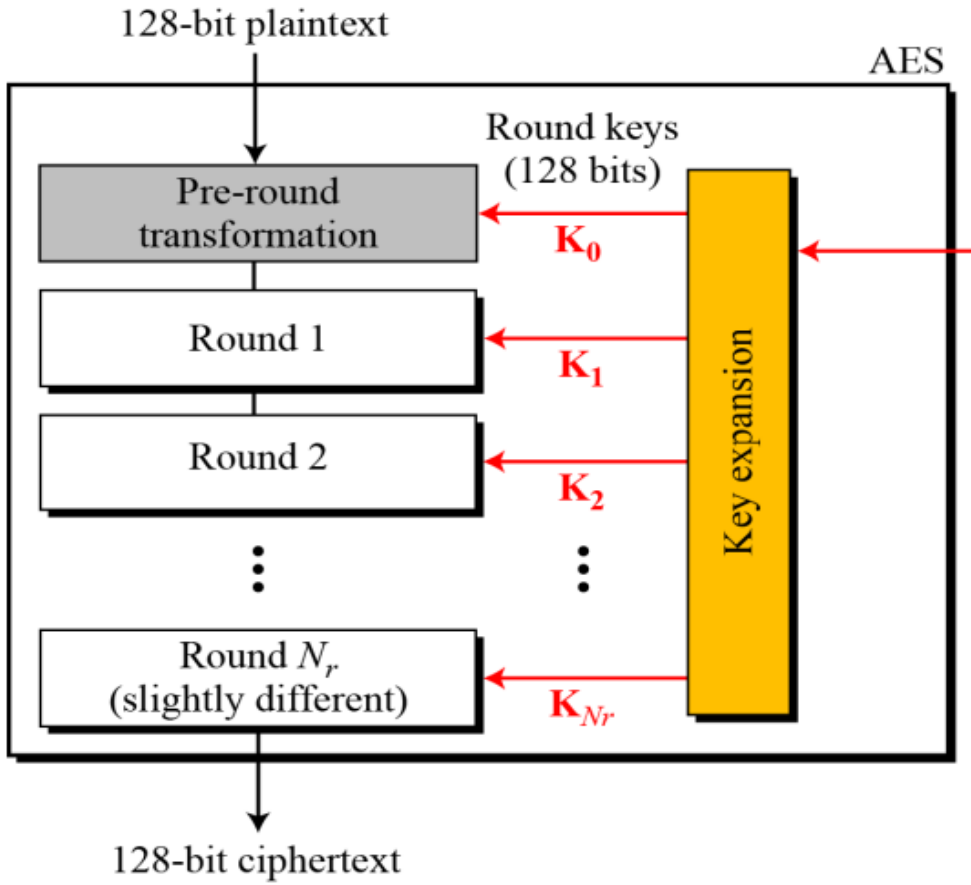
Always 128bits

Introduction

Rounds

The number of round key is one more than the number of rounds

Number of Round keys = Nr+1



Nr	Key size
10	128
12	192
14	256

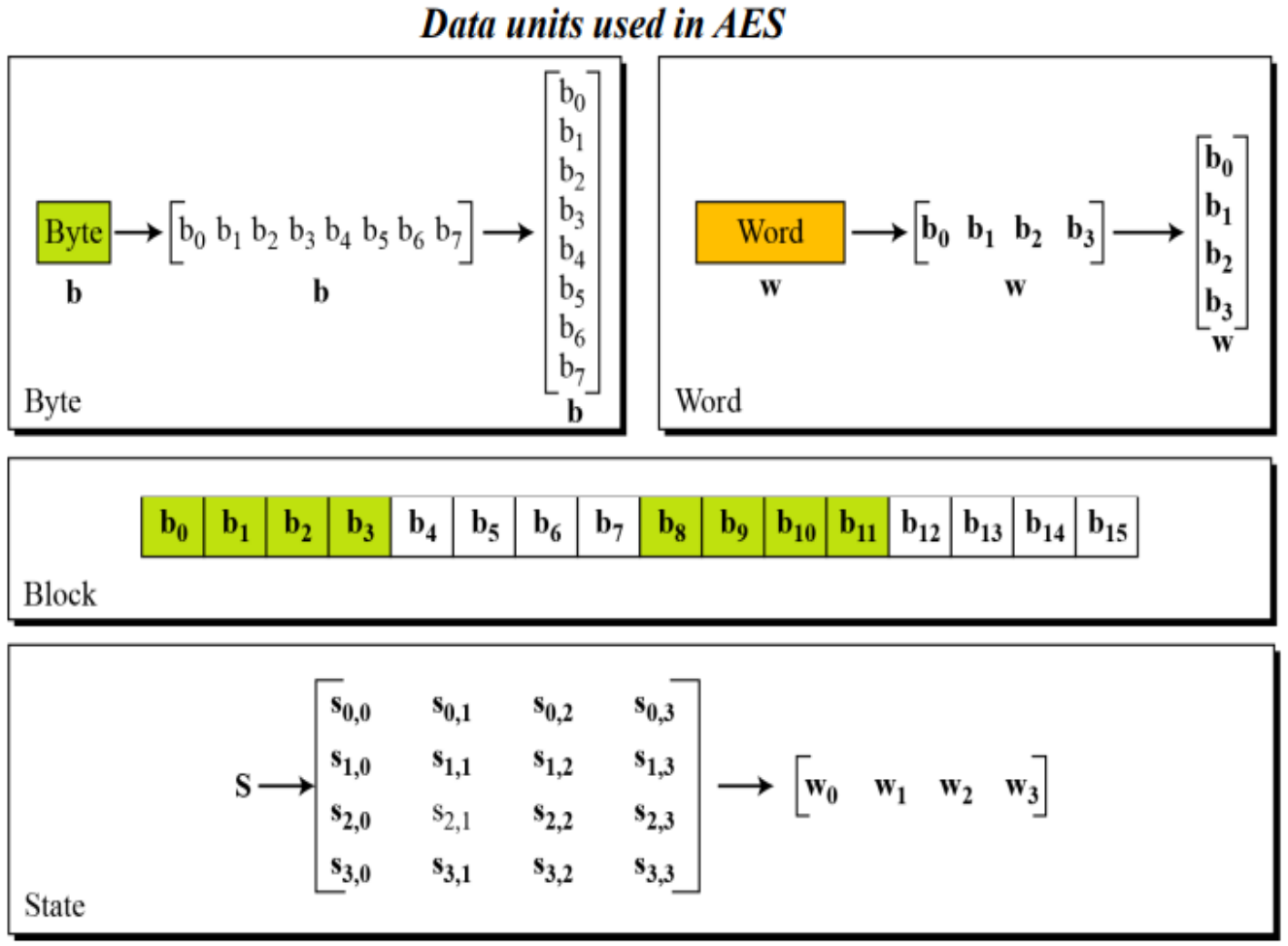
Relationship between number of rounds and cipher key size

Introduction

Data Units

AES uses 5 units of measurement to refer to data

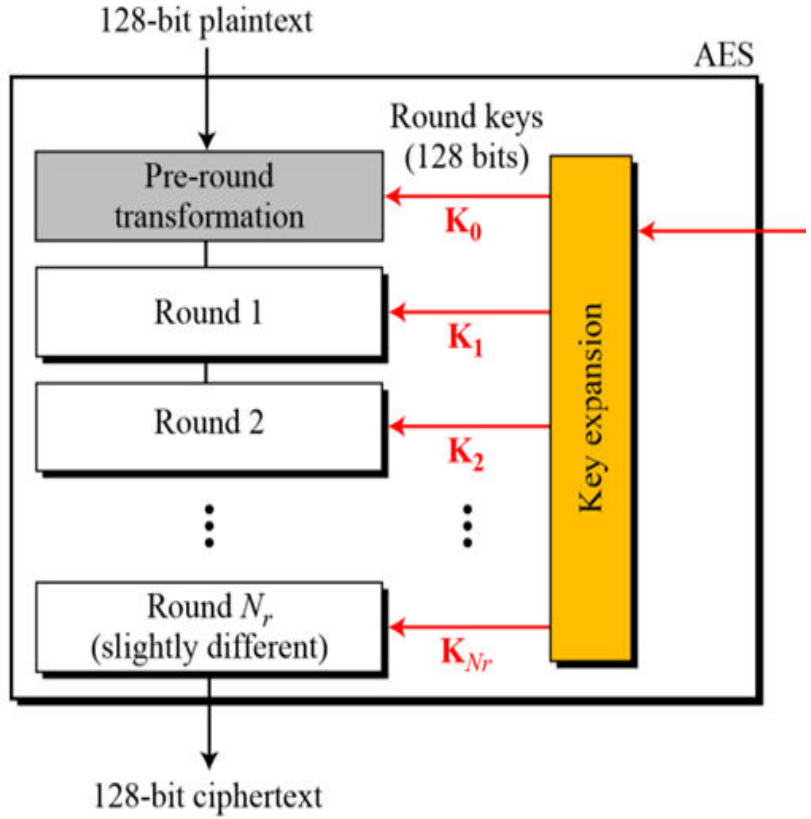
1. Bits
2. Bytes
3. Words
4. Blocks
5. State



Introduction

Data Units – States

- AES uses several rounds
- Each round is made of several stages – Data blocks are transferred from one stage to other
- At the beginning and end of cipher –data blocks
- Before and after each stage – data block is referred as state

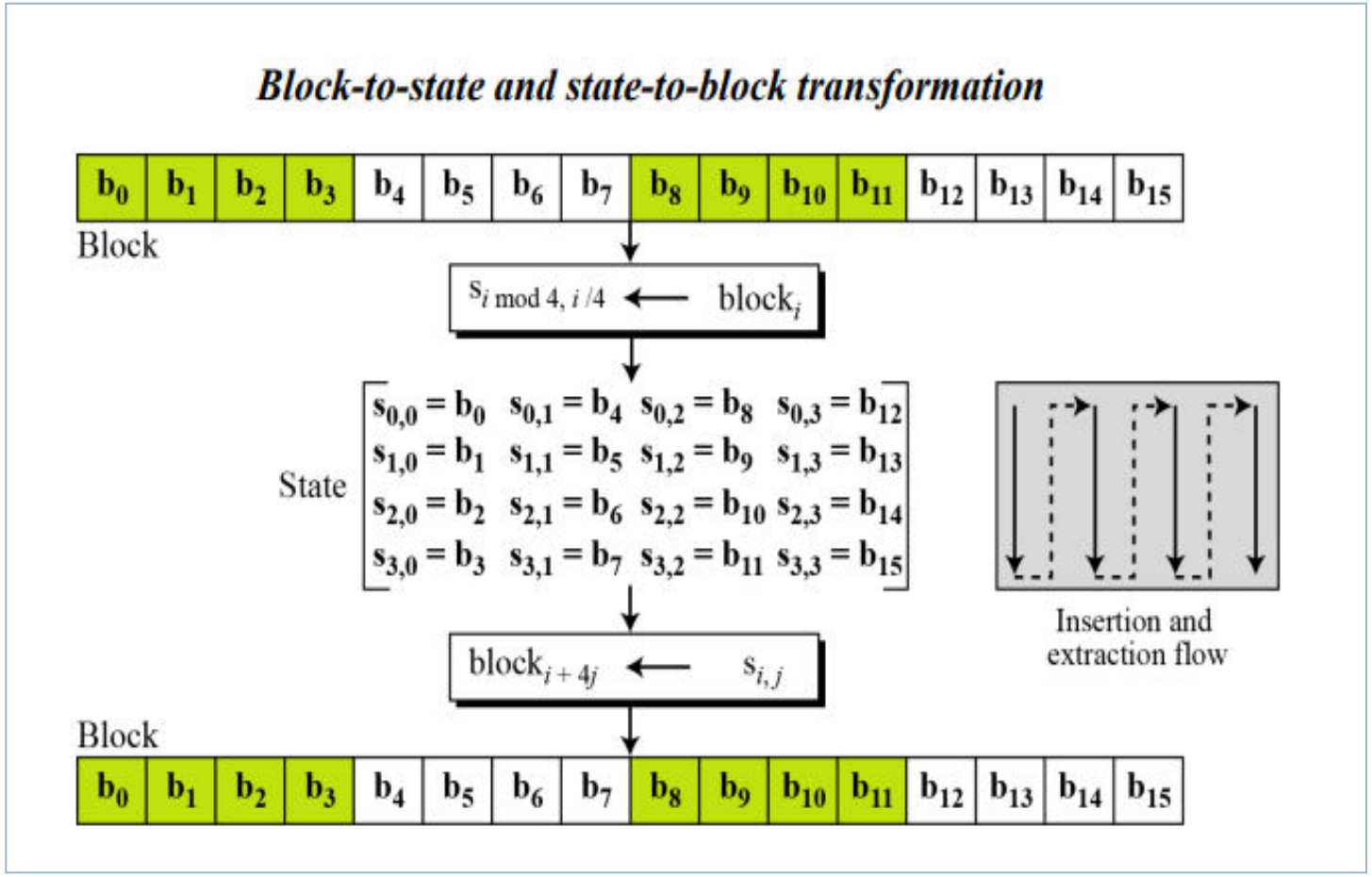


Introduction

Data Units – States

- S – State
- T- temporary state
- States are made up of 16bytes
- Matrix (4x4)

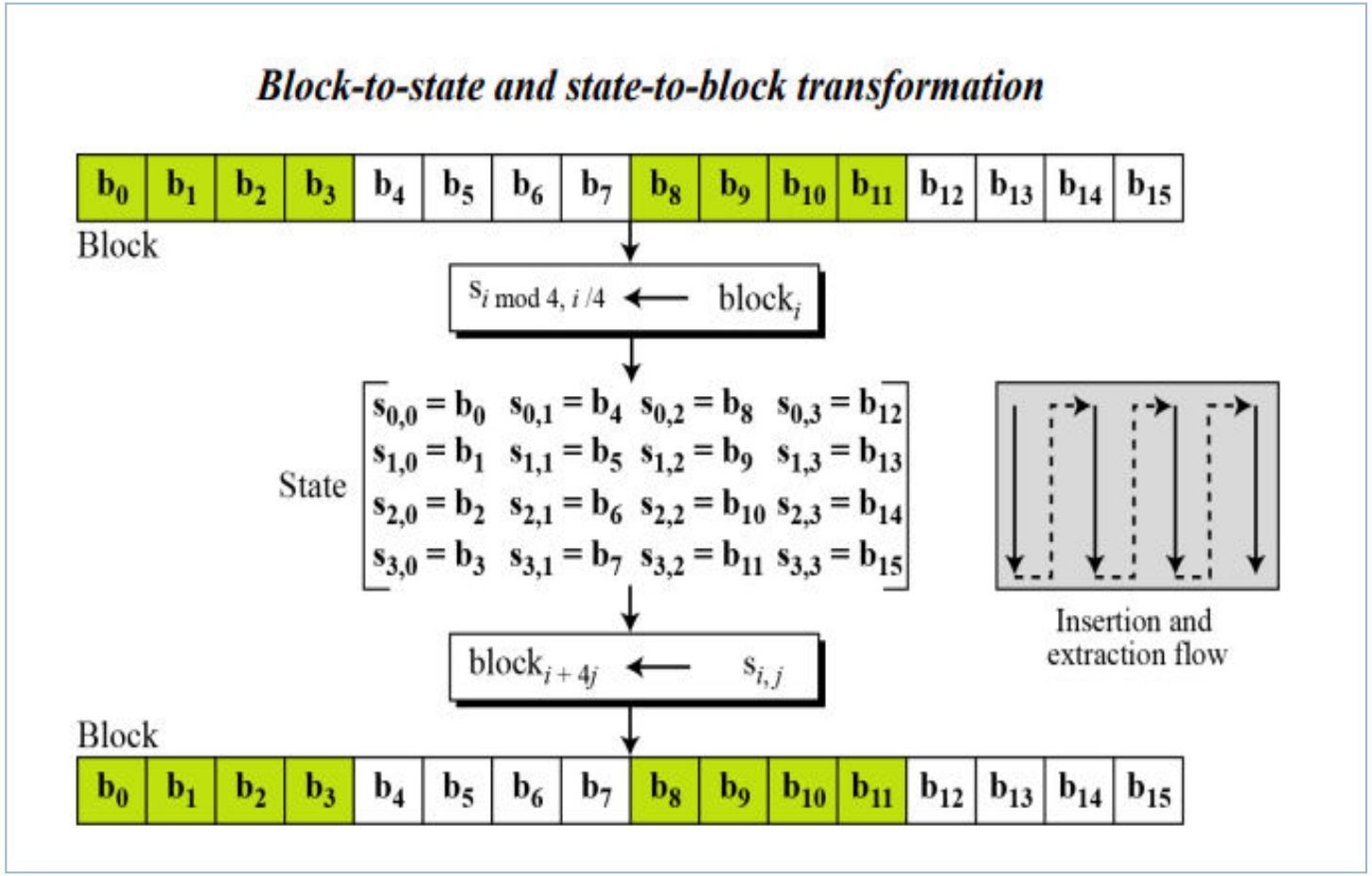
0	1	2	3
4	5	6	7
8	9	10	11
12	13	14	15



Introduction

Data Units – States

- Sate is treated as row matrix(1 x 4) of words



RAMAIAH Institute of Technology

Introduction

Example

Changing plaintext to state

Text	A	E	S	U	S	E	S	A	M	A	T	R	I	X	Z	Z
Hexadecimal	00	04	12	14	12	04	12	00	0C	00	13	11	08	23	19	19

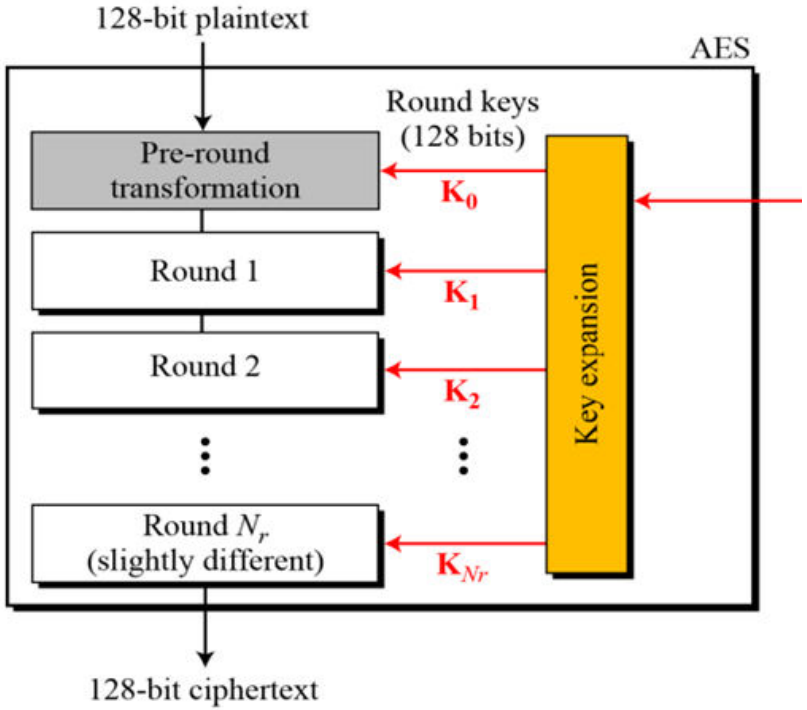
$$\begin{bmatrix} 00 & 12 & 0C & 08 \\ 04 & 04 & 00 & 23 \\ 12 & 12 & 13 & 19 \\ 14 & 00 & 11 & 19 \end{bmatrix}$$ State

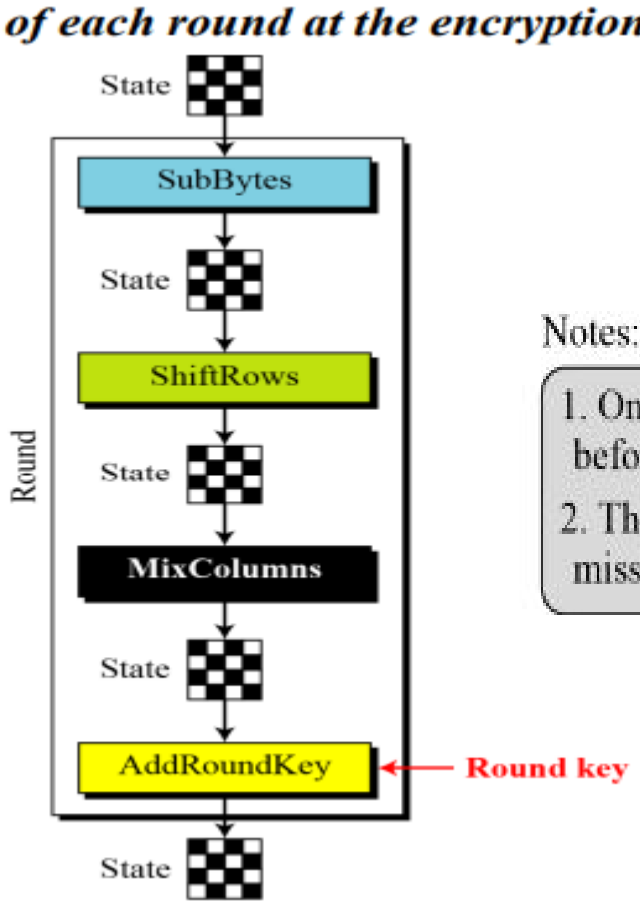
Plaintext →	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z
Ciphertext →	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
Value →	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25

Decimal	Hex	Char
0	0	[NULL]
1	1	[START OF HEADING]
2	2	[START OF TEXT]
3	3	[END OF TEXT]
4	4	[END OF TRANSMISSION]
5	5	[ENQUIRY]
6	6	[ACKNOWLEDGE]
7	7	[BELL]
8	8	[BACKSPACE]
9	9	[HORIZONTAL TAB]
10	A	[LINE FEED]
11	B	[VERTICAL TAB]
12	C	[FORM FEED]
13	D	[CARRIAGE RETURN]
14	E	[SHIFT OUT]
15	F	[SHIFT IN]
16	10	[DATA LINK ESCAPE]
17	11	[DEVICE CONTROL 1]
18	12	[DEVICE CONTROL 2]
19	13	[DEVICE CONTROL 3]
20	14	[DEVICE CONTROL 4]
21	15	[NEGATIVE ACKNOWLEDGE]
22	16	[SYNCHRONOUS IDLE]
23	17	[ENG OF TRANS. BLOCK]
24	18	[CANCEL]
25	19	[END OF MEDIUM]
26	1A	[SUBSTITUTE]
27	1B	[ESCAPE]
28	1C	[FILE SEPARATOR]
29	1D	[GROUP SEPARATOR]
30	1E	[RECORD SEPARATOR]
31	1F	[UNIT SEPARATOR]

Introduction

Structure of Round





Notes:

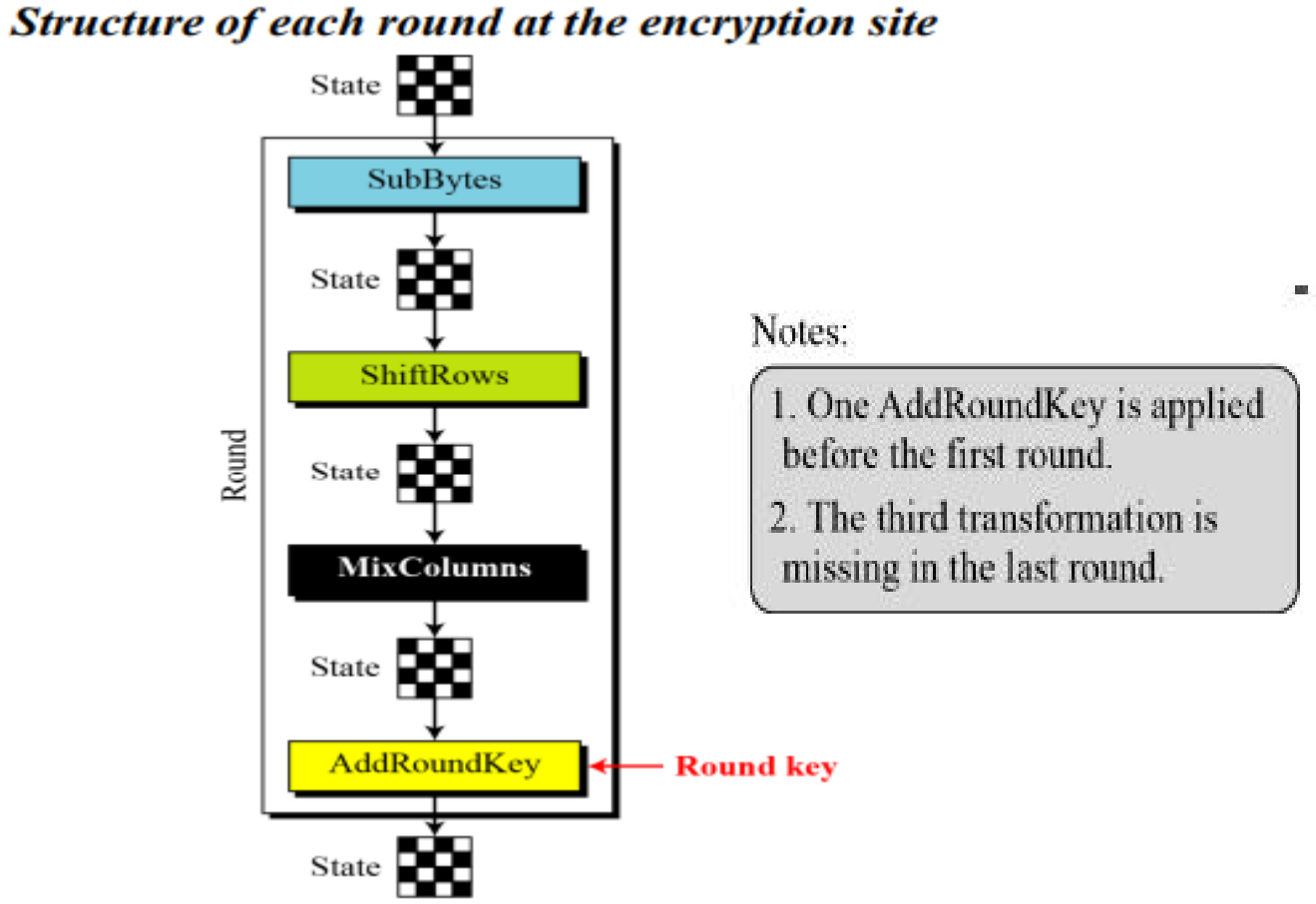
1. One AddRoundKey is applied before the first round.
2. The third transformation is missing in the last round.

Introduction

Structure of Round

4 Transformations

1. SubBytes
2. ShiftRows
3. MixColumns
4. Add Round Keys



Transformation

1. SubBytes(Substitution)
2. ShiftRows (Permutation)
3. MixColumns (Mixing)
4. Add Round Keys (Adding)

Transformation

SubBytes(Substitution)

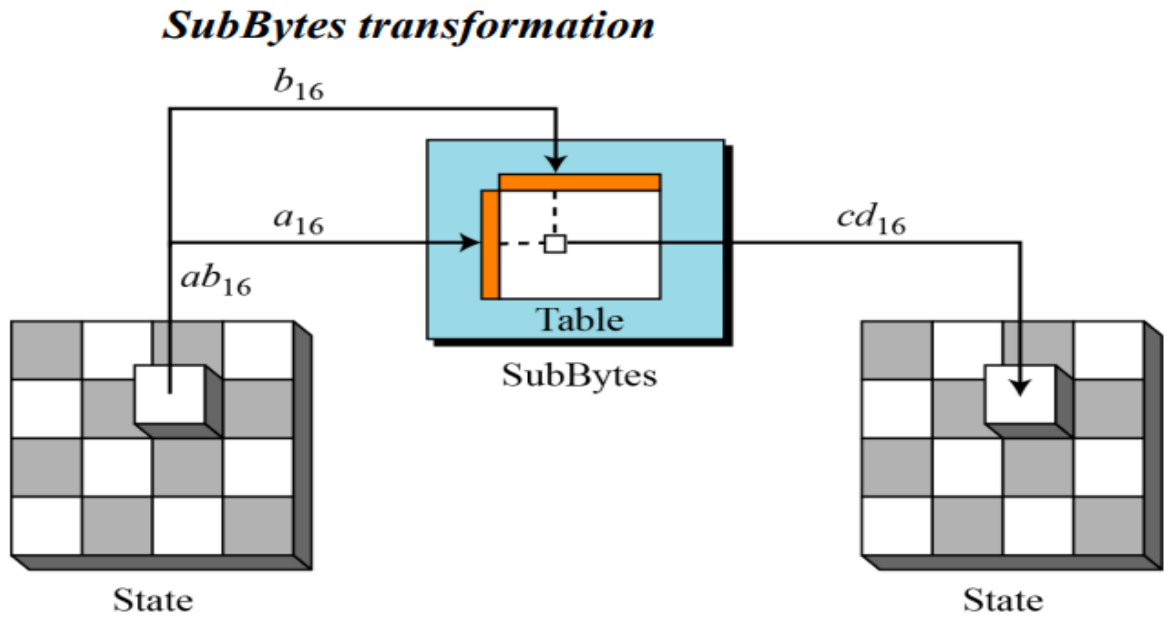
- AES uses substitution
- Mechanism is different
  1. Substitution done for each byte
  2. Table is used for substitution for each byte
  3. Table Lookup process or mathematical calculation in GF(2^8 field)

RAMAIAH Institute of Technology

Transformation

SubBytes

- SubBytes is used at the encryption site.
- To substitute a byte, we interpret the byte as two hexadecimal digits.
- Left digit –row
- Right digit -column



RAMAIAH Institute of Technology

Transformation

SubBytes- Transformation table

SubBytes transformation table

	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	CB	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

InvSubBytes-Transformation table

	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

RAMAIAH Institute of Technology

Transformation

Example 1

$5A_{16} = BE_{16}$

$5B_{16} = 39_{16}$

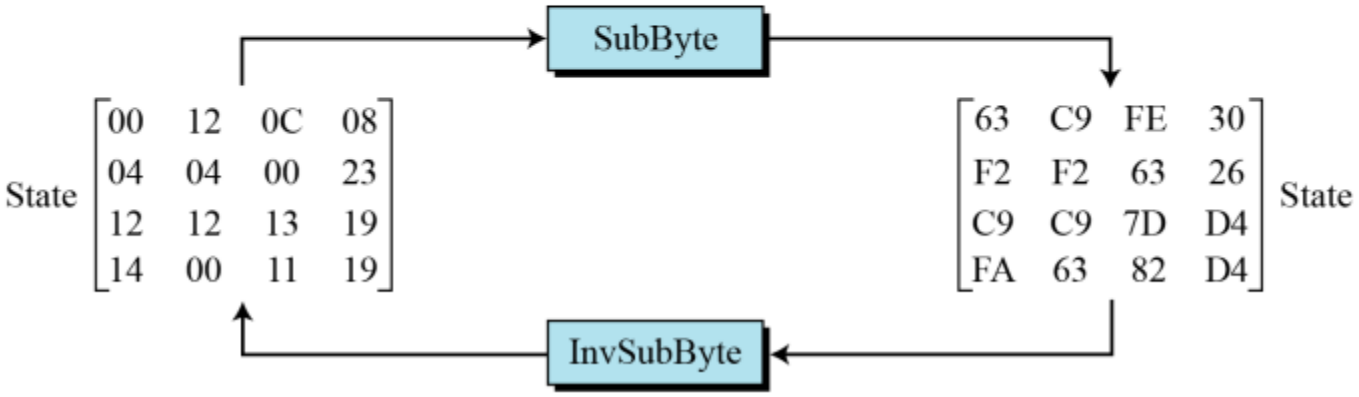
SubBytes transformation table

	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	CB	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

Transformation

Example 2

shows how a state is transformed using the SubBytes transformation. The figure also shows that the InvSubBytes transformation creates the original one. Note that if the two bytes have the same values, their transformation is also the same.



	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

Transformation

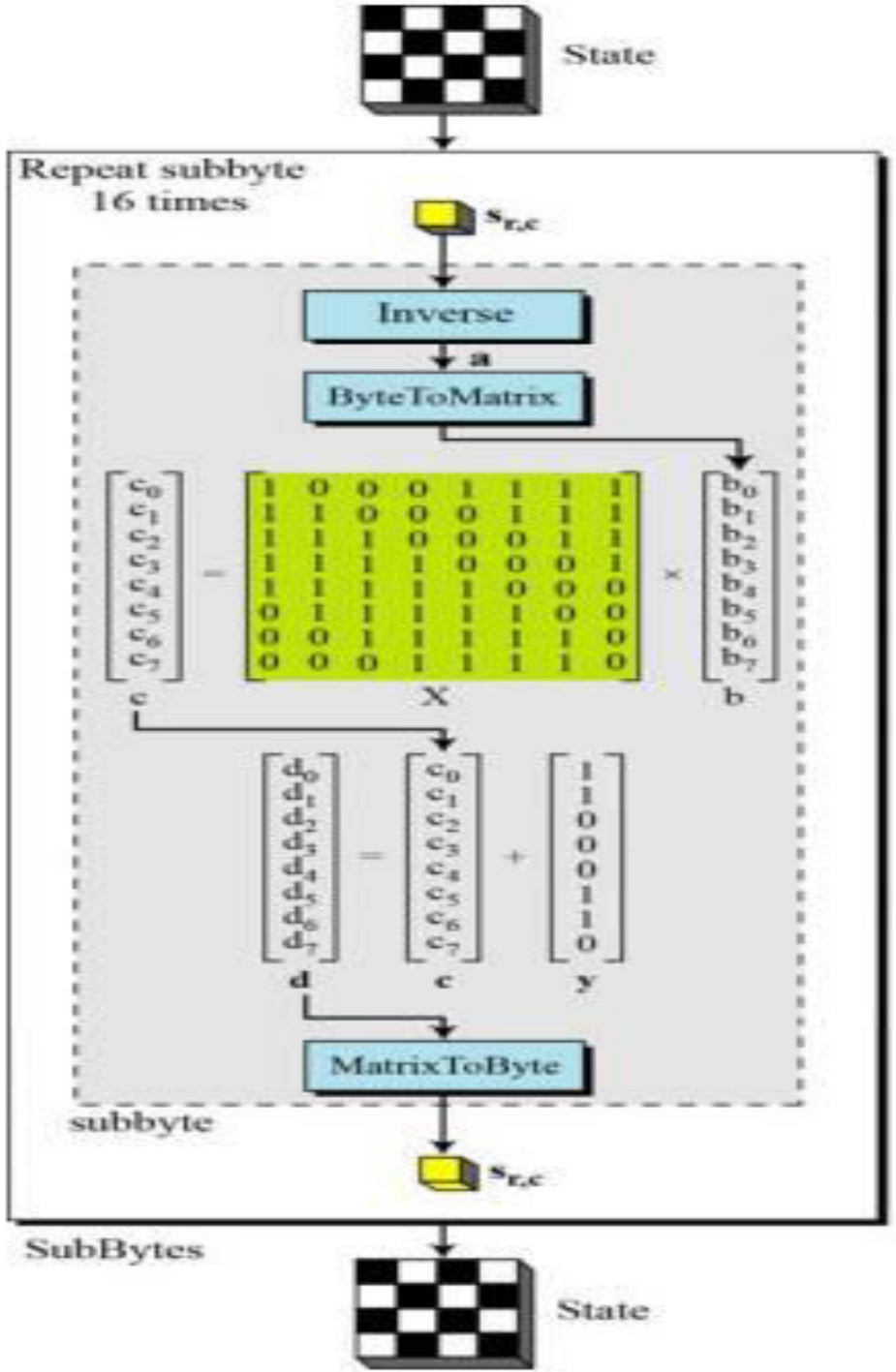
SubBytes

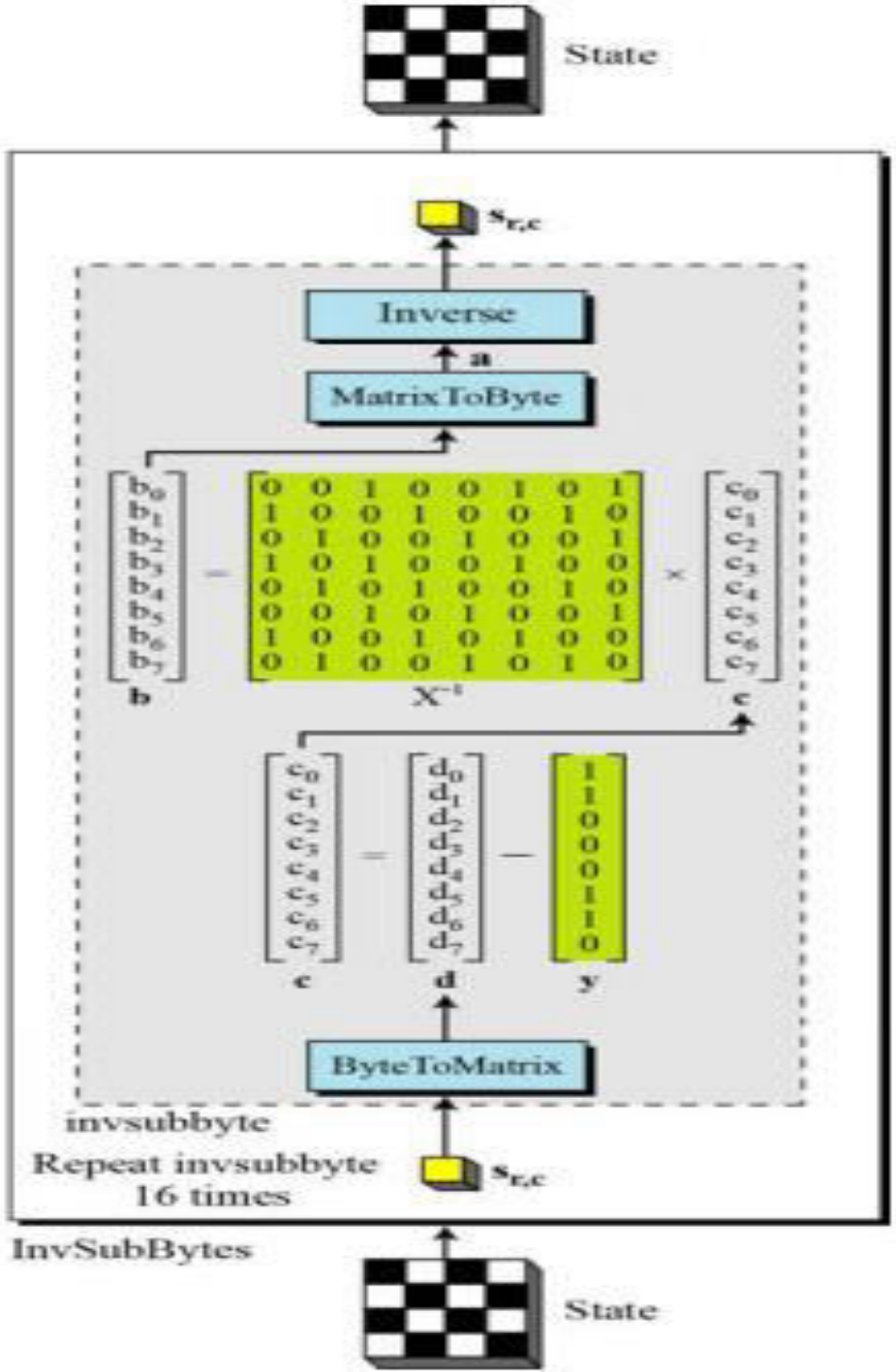
Transformation Using the GF(2^8) Field

AES also defines the transformation algebraically using the GF(28) field with the irreducible polynomials ($x^8 + x^4 + x^3 + x + 1$)

subbyte: $\rightarrow \quad \mathbf{d} = \mathbf{X}\,(s_{r,c})^{-1} \oplus \mathbf{y}$

invsubbyte: $\rightarrow \quad [\mathbf{X}^{-1}(\mathbf{d} \oplus \mathbf{y})]^{-1} = [\mathbf{X}^{-1}(\mathbf{X}\,(s_{r,c})^{-1} \oplus \mathbf{y} \oplus \mathbf{y})]^{-1} = [(s_{r,c})^{-1}]^{-1} = s_{r,c}$


State
Repeat subbyte
16 times
$s_{r,c}$
Inverse
a
ByteToMatrix
X
b
c
d
y
MatrixToByte
subbyte
$s_{r,c}$
SubBytes
State


State
$s_{r,c}$
Inverse
a
MatrixToByte
X^{-1}
b
c
d
y
ByteToMatrix
invsubbyte
Repeat invsubbyte
16 times
$s_{r,c}$
InvSubBytes
State

Transformation

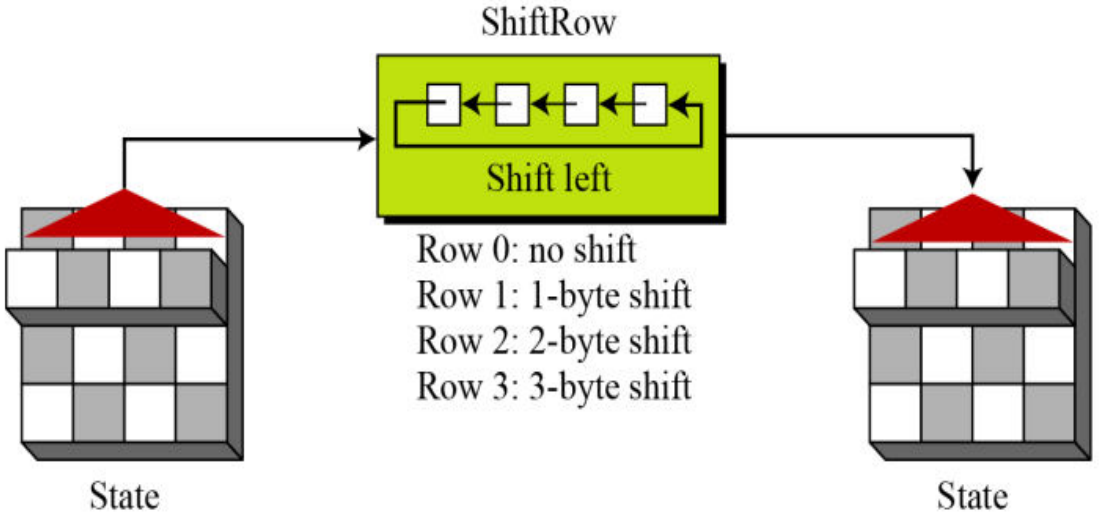
Pseudocode for SubBytes transformation

```
SubBytes (S)
{
   for (r = 0 to 3)
     for (c = 0 to 3)
           S_r,c = subbyte (S_r,c)
}

subbyte (byte)
{
   a ← byte^-1              // Multiplicative inverse in GF(2^8) with inverse of 00 to be 00
    ByteToMatrix (a, b)
    for (i = 0 to 7)
    {
        c_i ← b_i ⊕ b_(i+4)mod 8 ⊕ b_(i+5)mod 8 ⊕ b_(i+6)mod 8 ⊕ b_(i+7)mod 8
        d_i ← c_i ⊕ ByteToMatrix (0x63)
   }
    MatrixToByte (d, d)
    byte ← d
}
```

Transformation

ShiftRows (Permutation)

- Another transformation found in a round is shifting, which permutes the bytes.
- Each row is shifted a particular number of times.



[b0	b1	b2	b3]		[b0	b1	b2	b3]
b4	b5	b6	b7	->	b5	b6	b7	b4
b8	b9	b10	b11		b10	b11	b8	b9
[b12	b13	b14	b15]		[b15	b12	b13	b14]

Transformation

ShiftRows (Permutation)

- InvShiftRows In the decryption, the transformation is called InvShiftRows and the shifting is to the right.

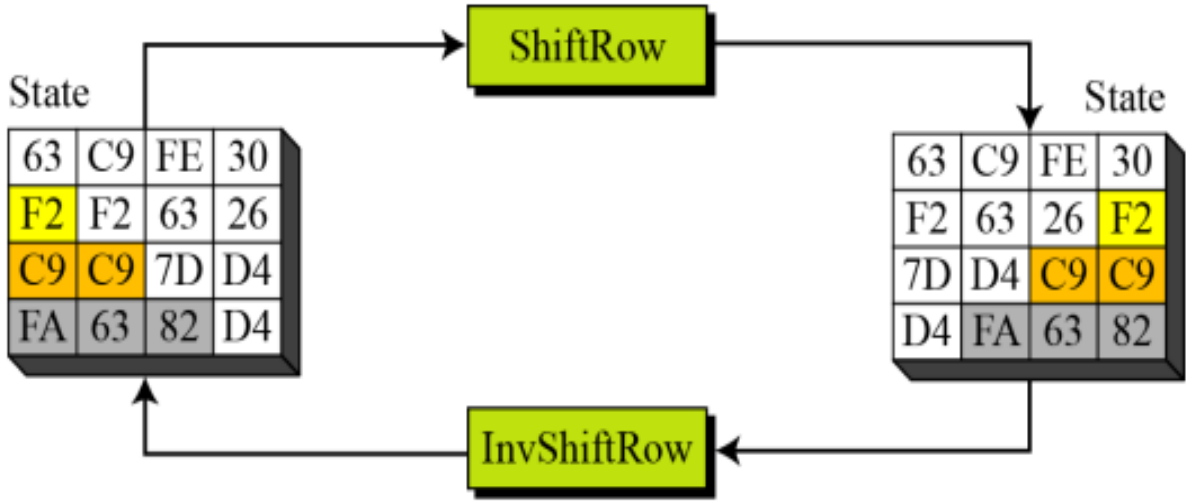
Pseudocode for ShiftRows transformation

```
ShiftRows (S)
{
    for (r = 1 to 3)
        shiftrow (s_r, r)                    // s_r is the rth row
}
shiftrow (row, n)                            // n is the number of bytes to be shifted
{
   CopyRow (row, t)                          // t is a temporary row
   for (c = 0 to 3)
        row_((c – n) mod 4) ← t_c
}
```

Transformation

ShiftRows (Permutation)

shows how a state is transformed using ShiftRows transformation. The figure also shows that InvShiftRows transformation creates the original state.

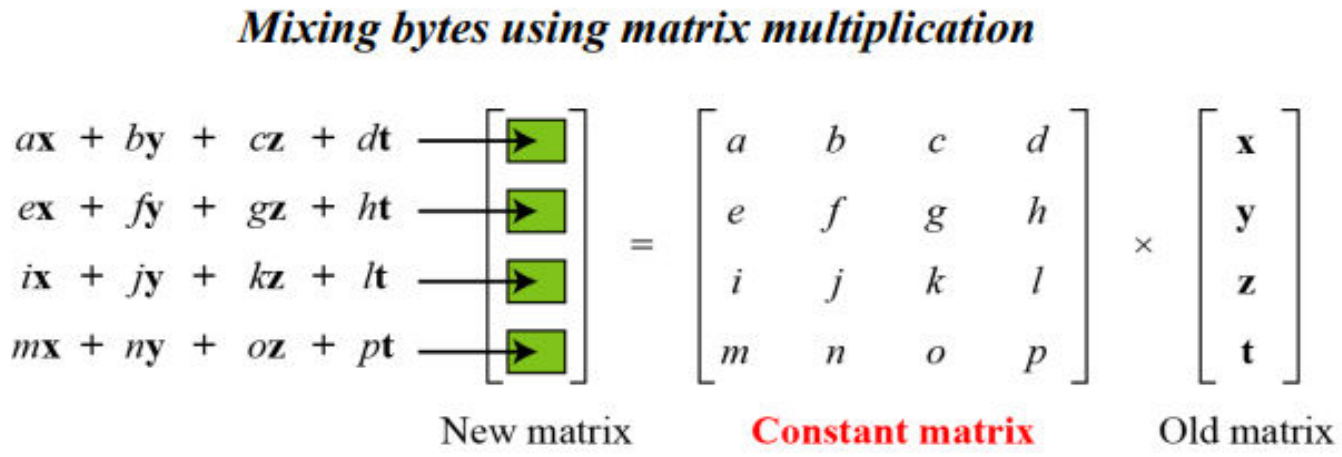


[b0	b1	b2	b3]		[b0	b1	b2	b3]
| b4	b5	b6	b7 |	->	| b5	b6	b7	b4 |
| b8	b9	b10	b11 |		| b10	b11	b8	b9 |
[b12	b13	b14	b15]		[b15	b12	b13	b14]

Transformation

MixColumns (Mixing)

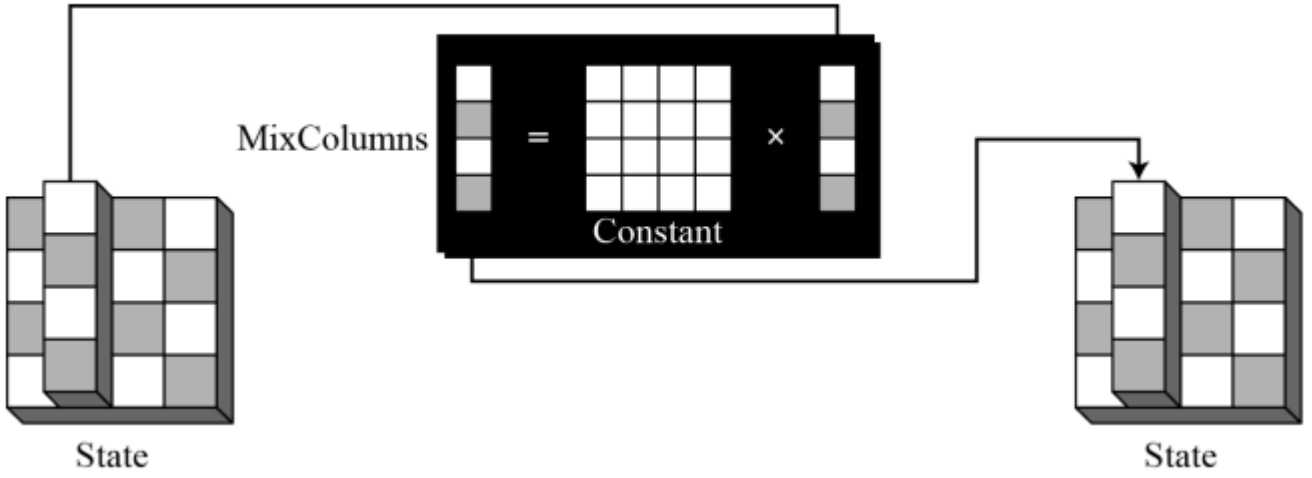
- This step is basically a matrix multiplication.
- Each column is multiplied with a specific matrix and thus the position of each byte in the column is changed as a result.



Transformation

MixColumns (Mixing)

- The MixColumns transformation operates at the column level; it transforms each column of the state to a new column.



Transformation

MixColumns (Mixing)

Pseudocode for MixColumns transformation

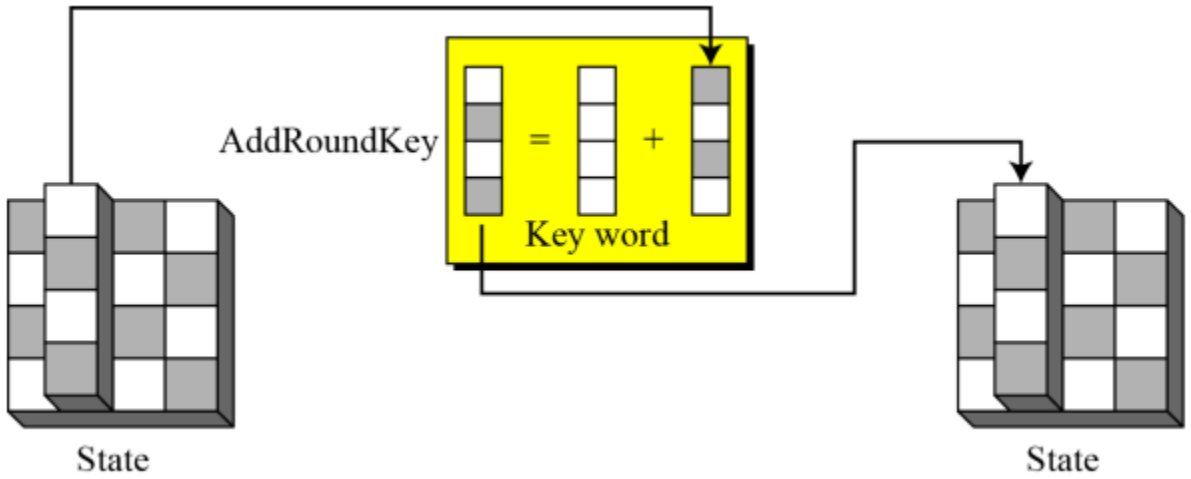
```
MixColumns (S)
{
    for (c = 0 to 3)
        mixcolumn (s_c)
}

mixcolumn (col)
{
   CopyColumn (col, t)                    // t is a temporary column

   col_0 ← (0x02) • t_0 ⊕ (0x03 • t_1) ⊕ t_2 ⊕ t_3

   col_1 ← t_0 ⊕ (0x02) • t_1 ⊕ (0x03) • t_2 ⊕ t_3

   col_2 ← t_0 ⊕ t_1 ⊕ (0x02) • t_2 ⊕ (0x03) • t_3

   col_3 ← (0x03 • t_0) ⊕ t_1 ⊕ t_2 ⊕ (0x02) • t_3
}
```

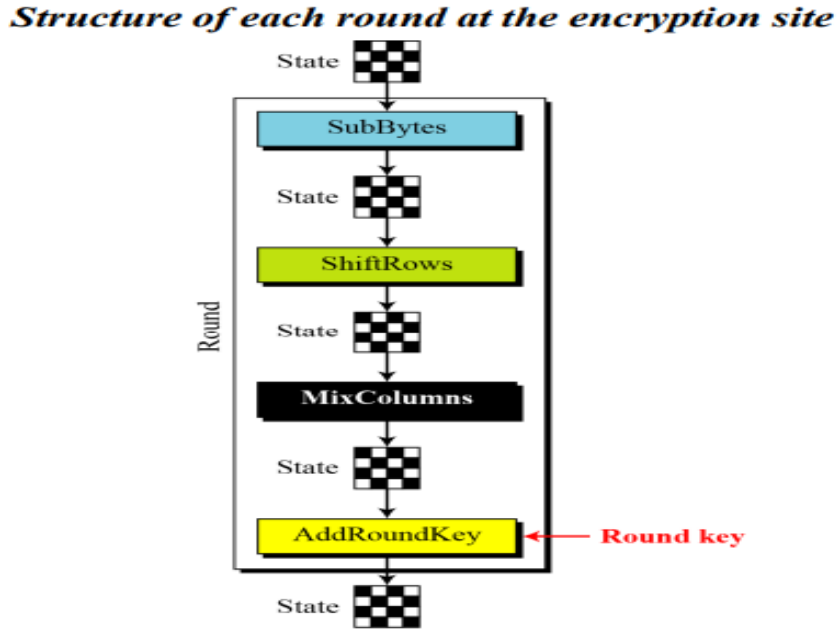
RAMAIAH Institute of Technology

Transformation

Add Round Keys (Adding)

- AddRoundKey proceeds one column at a time.
- AddRoundKey adds a round key word with each state column matrix; the operation in AddRoundKey is matrix addition.





Transformation

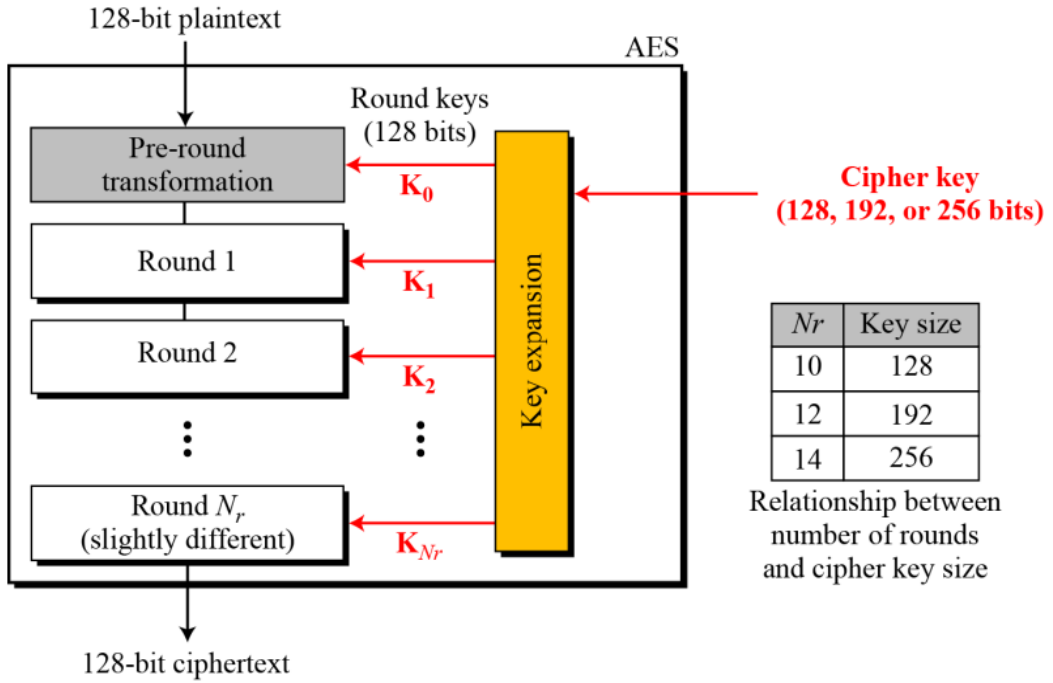
Add Round Keys (Adding)

Pseudocode for AddRoundKey transformation

```
AddRoundKey (S)
{
    for (c = 0 to 3)
        s_c ← s_c ⊕ w_round + 4c
}
```

Key Expansion

- To create round keys for each round, AES uses a key-expansion process.
- If the number of rounds is Nr , the key-expansion routine creates Nr + 1 128-bit round keys from one single 128-bit cipher key

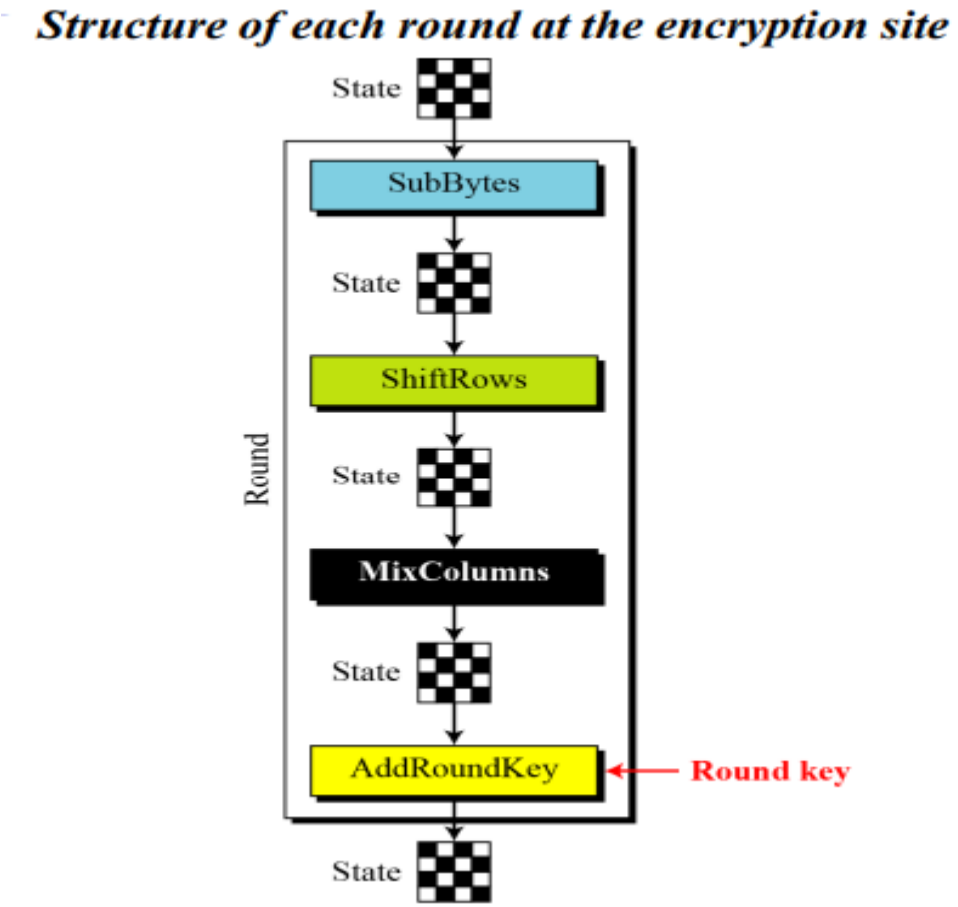


Nr	Key size
10	128
12	192
14	256

Relationship between number of rounds and cipher key size

Key Expansion

- First round key is used for pre-round transformation
- Remaining all for every round 4^{th} transformation



RAMAIAH Institute of Technology

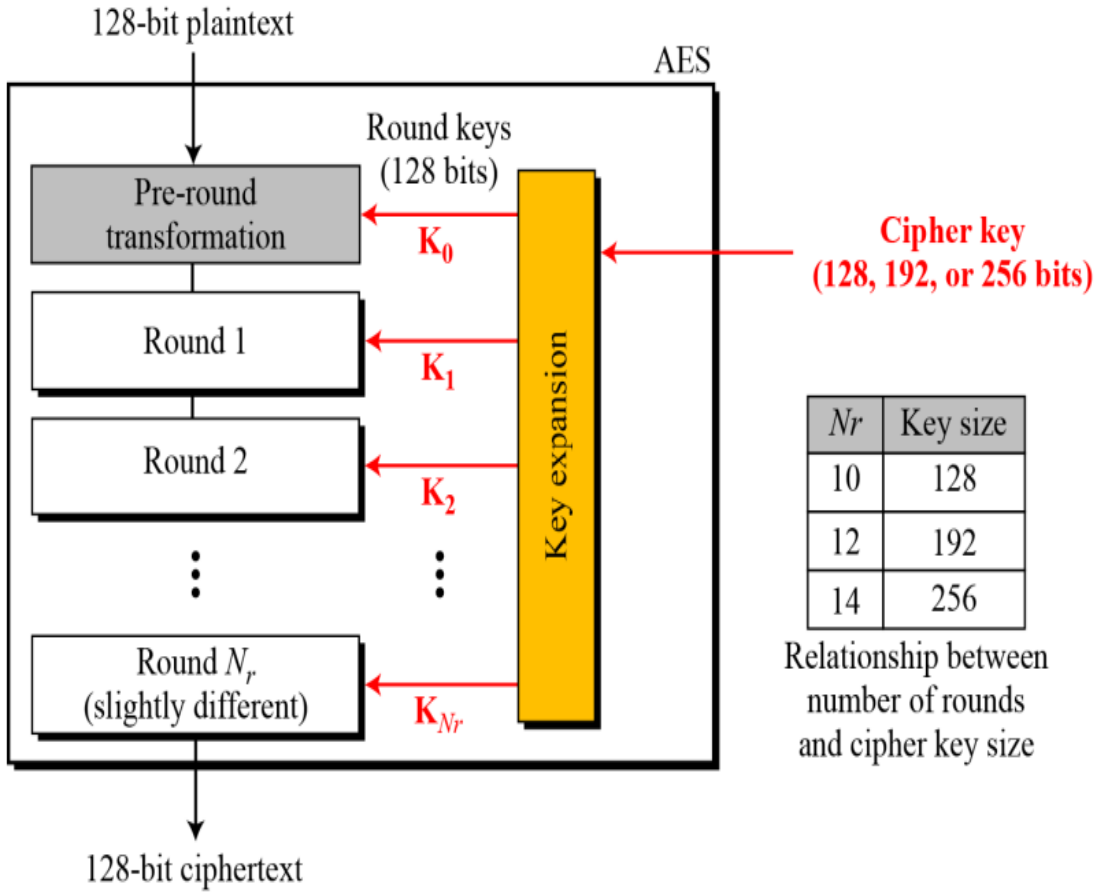
Key Expansion

Key-expansion creates round key word by word, where a word is an array of 4 bytes.

- Key Expansion in AES-128
- Key Expansion in AES-192 and AES-256
- Key-Expansion Analysis

Words for each round

Round	*Words*			
Pre-round	w_0	w_1	w_2	w_3
1	w_4	w_5	w_6	w_7
2	w_8	w_9	w_{10}	w_{11}
. . .	. . .			
N_r	w_{4N_r}	w_{4N_r+1}	w_{4N_r+2}	w_{4N_r+3}



Nr	Key size
10	128
12	192
14	256

Relationship between number of rounds and cipher key size

RAMAIAH
Institute of Technology

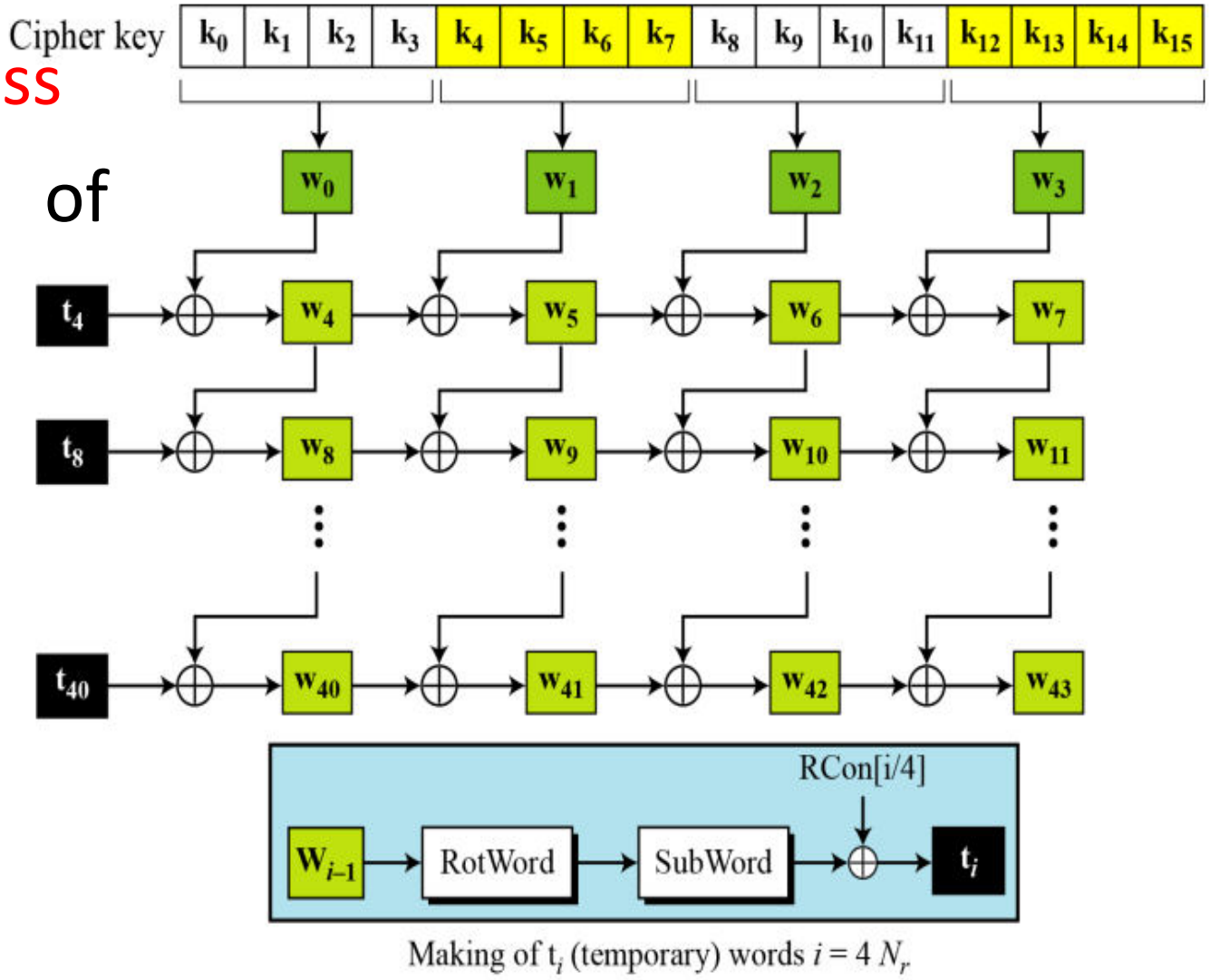
Key Expansion

Key Expansion in AES-128 process

1. Cipher key is an array of 16bytes(k0 to k15)

   The first 4 words(w0,w1,w2,w3) are made from cipher key

   - K0 to k3 -> w0
   - k4 to k7 -> w1
   - K8 to k11 ->w2
   - K12 to k15 ->w3



Making of t_i (temporary) words $i = 4\ N_r$

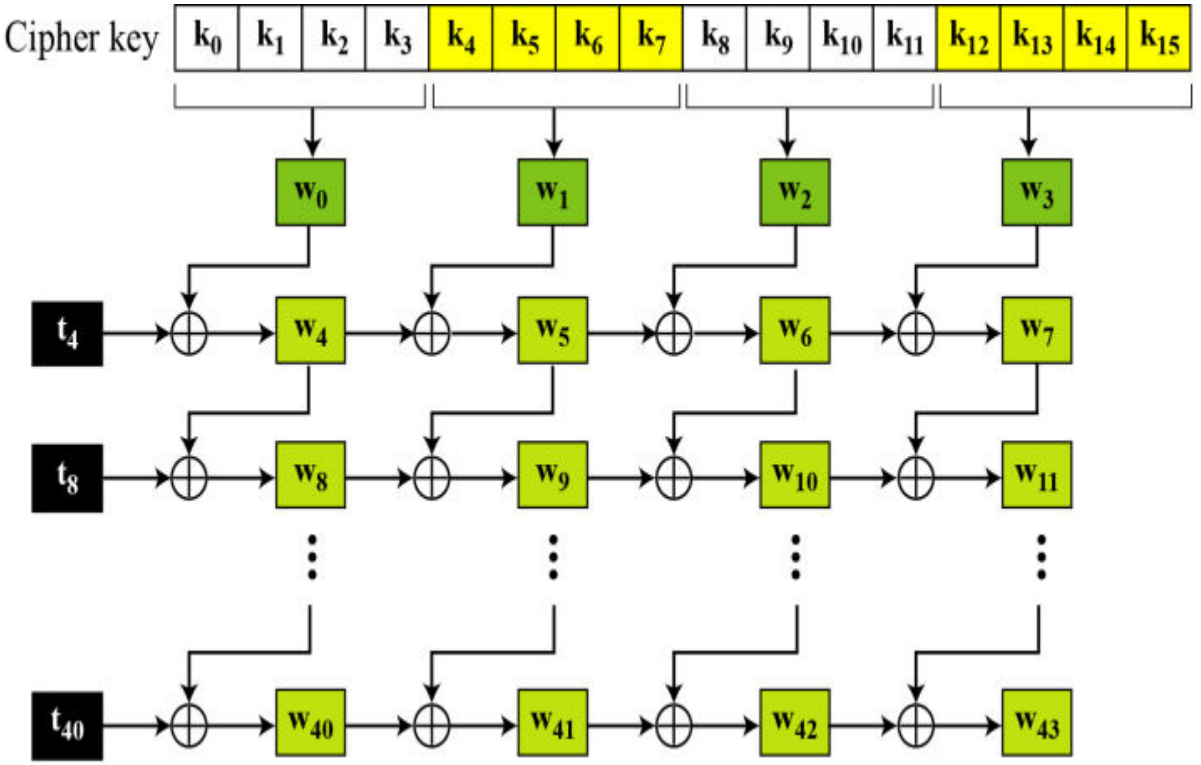
Key Expansion

Key Expansion in AES-128 process

2. The rest of the words (w_i for i : are made as follows

i) if (i mod 4) ≠ 0, $w_i = w_{i-1} \oplus w_{i-4}$

ii) if (i mod 4) = 0, $w_i = t \oplus w_{i-4}$



Temporary word t

$t_i = subword(Rotword(w_{i-1})) \oplus Rcon_{i/4}$

Key Expansion

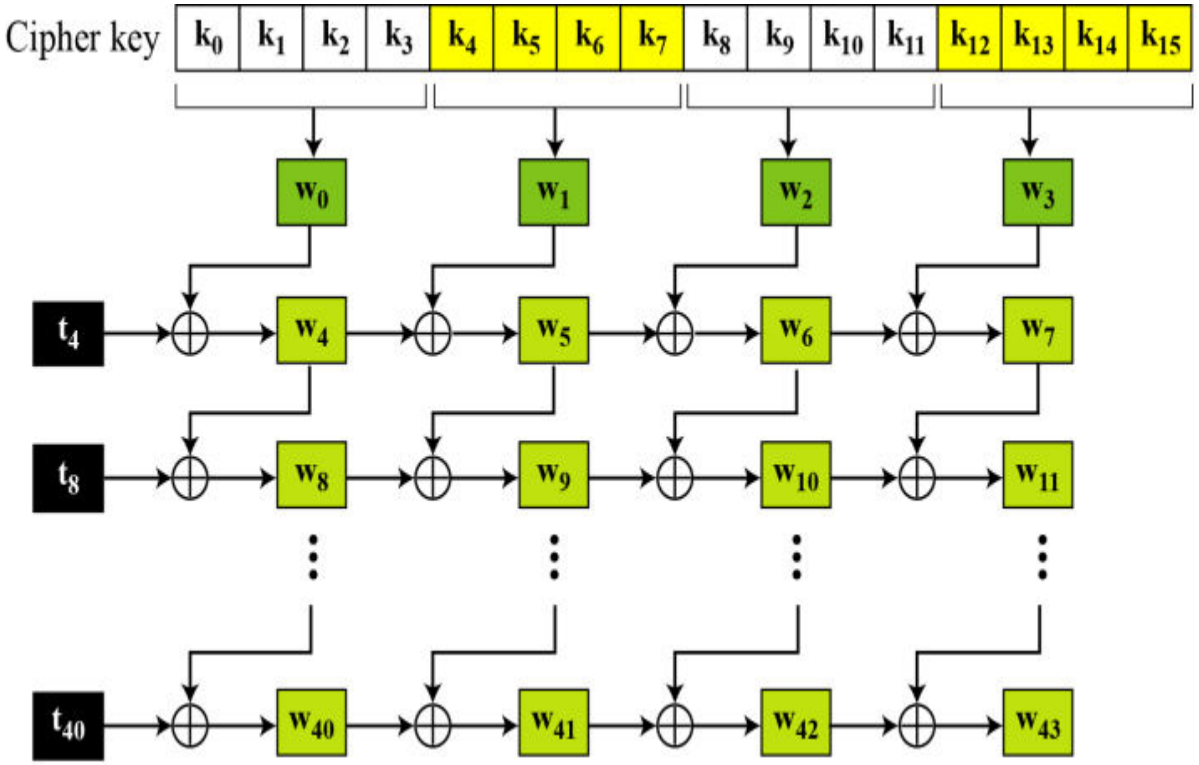
$t_i = subword(Rotword(w_{i-1})) \oplus Rcon_{i/4}$

Rotword : Applied to only one row

Rotate word routine takes a word as an array of 4bytes and shifts each byte to the left with wrapping.

Subword : Applied to 4 bytes.

Substitute word routine takes each byte in the word and substitute another byte for it.



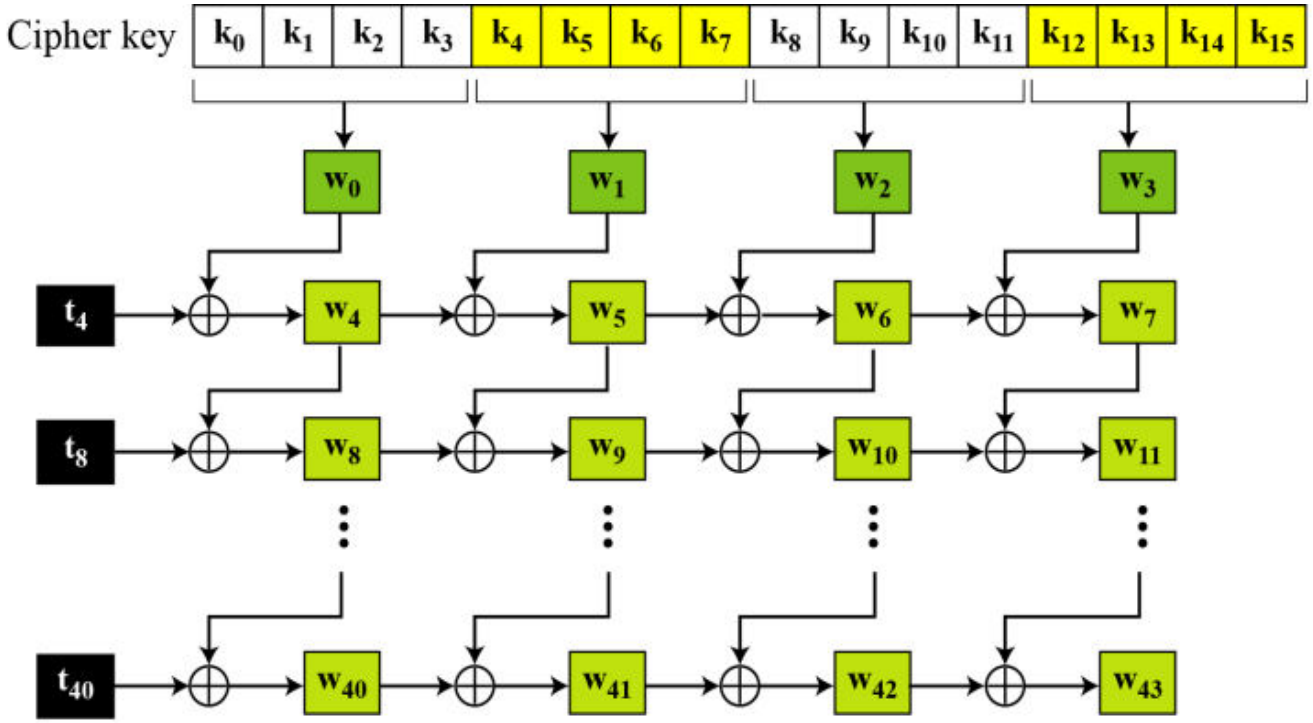
RAMAIAH Institute of Technology

Key Expansion

$t_i = subword(Rotword(w_{i-1})) \oplus Rcon_{i/4}$

Rcon : Round constant is a 4byte value in which the rightmost 3bytes are always zero

Round	*Constant (RCon)*	*Round*	*Constant (RCon)*
1	(**01** 00 00 00)$_{16}$	6	(**20** 00 00 00)$_{16}$
2	(**02** 00 00 00)$_{16}$	7	(**40** 00 00 00)$_{16}$
3	(**04** 00 00 00)$_{16}$	8	(**80** 00 00 00)$_{16}$
4	(**08** 00 00 00)$_{16}$	9	(**1B** 00 00 00)$_{16}$
5	(**10** 00 00 00)$_{16}$	10	(**36** 00 00 00)$_{16}$



Key Expansion

The key-expansion routine can either use the table when calculating the words or use the GF(2^8) field to calculate the leftmost byte dynamically, as shown below

RC_1	$\rightarrow x^{1-1}$	$= x^0$	mod *prime*	$= 1$	$\rightarrow 00000001$	$\rightarrow 01_{16}$
RC_2	$\rightarrow x^{2-1}$	$= x^1$	mod *prime*	$= x$	$\rightarrow 00000010$	$\rightarrow 02_{16}$
RC_3	$\rightarrow x^{3-1}$	$= x^2$	mod *prime*	$= x^2$	$\rightarrow 00000100$	$\rightarrow 04_{16}$
RC_4	$\rightarrow x^{4-1}$	$= x^3$	mod *prime*	$= x^3$	$\rightarrow 00001000$	$\rightarrow 08_{16}$
RC_5	$\rightarrow x^{5-1}$	$= x^4$	mod *prime*	$= x^4$	$\rightarrow 00010000$	$\rightarrow 10_{16}$
RC_6	$\rightarrow x^{6-1}$	$= x^5$	mod *prime*	$= x^5$	$\rightarrow 00100000$	$\rightarrow 20_{16}$
RC_7	$\rightarrow x^{7-1}$	$= x^6$	mod *prime*	$= x^6$	$\rightarrow 01000000$	$\rightarrow 40_{16}$
RC_8	$\rightarrow x^{8-1}$	$= x^7$	mod *prime*	$= x^7$	$\rightarrow 10000000$	$\rightarrow 80_{16}$
RC_9	$\rightarrow x^{9-1}$	$= x^8$	mod *prime*	$= x^4 + x^3 + x + 1$	$\rightarrow 00011011$	$\rightarrow 1B_{16}$
RC_{10}	$\rightarrow x^{10-1}$	$= x^9$	mod *prime*	$= x^5 + x^4 + x^2 + x$	$\rightarrow 00110110$	$\rightarrow 36_{16}$

Key Expansion

Key Expansion in AES-128 - Algorithm

KeyExpansion ([key_0 to key_{15}], [$\mathbf{w}_0$ **to** $\mathbf{w}_{43}$])

```
{
    for (i = 0 to 3)
        w_i ← key_4i + key_4i+1 + key_4i+2 + key_4i+3

    for (i = 4 to 43)
    {
        if (i mod 4 ≠ 0)    w_i ← w_i−1 + w_i−4
        else
        {
            t ← SubWord (RotWord (w_i−1)) ⊕ RCon_i/4
            w_i ← t + w_i−4
        }
    }
}
```

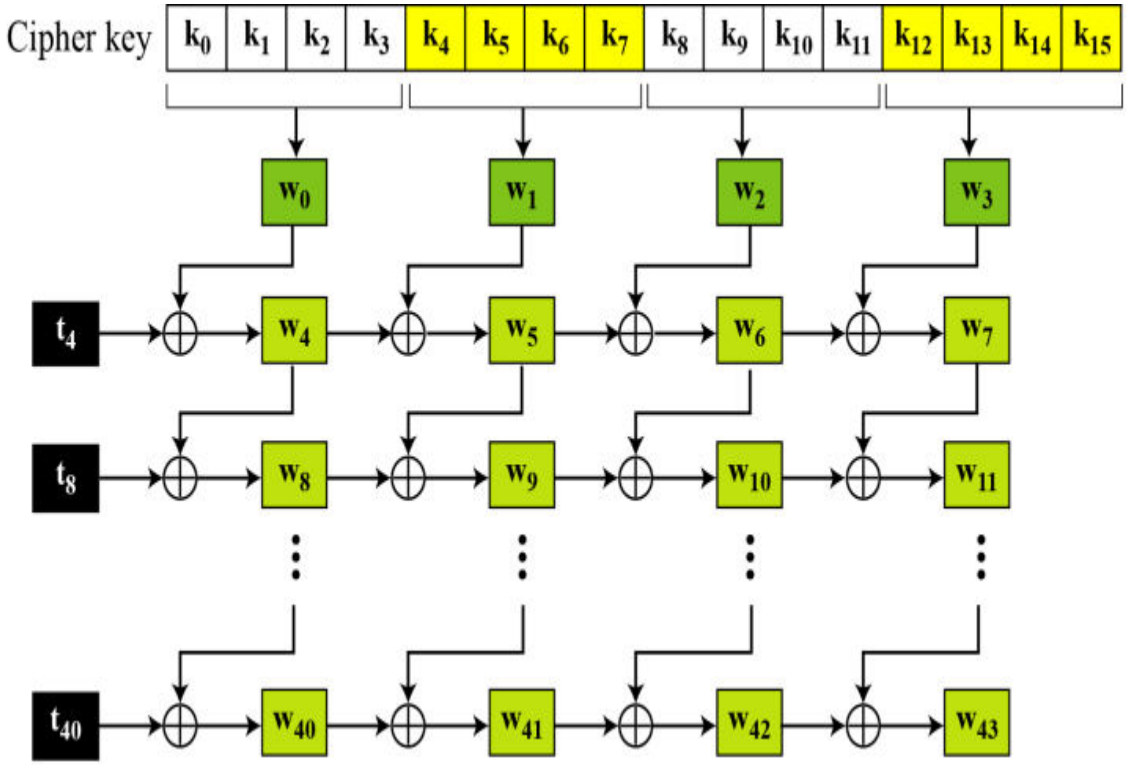
RAMAIAH Institute of Technology

Key Expansion

Table 7.5 shows how the keys for each round are calculated assuming that the 128-bit cipher key agreed upon by Alice and Bob is (24 75 A2 B3 34 75 56 88 31 E2 12 00 13 AA 54 87)$_{16}$.

Table 7.5 *Key expansion example*

Round	*Values of t's*	*First word in the round*	*Second word in the round*	*Third word in the round*	*Fourth word in the round*
—		w_{00} = 2475A2B3	w_{01} = 34755688	w_{02} = 31E21200	w_{03} = 13AA5487
1	AD20177D	w_{04} = 8955B5CE	w_{05} = BD20E346	w_{06} = 8CC2F146	w_{07} = 9F68A5C1
2	470678DB	w_{08} = CE53CD15	w_{09} = 73732E53	w_{10} = FFB1DF15	w_{11} = 60D97AD4
3	31DA48D0	w_{12} = FF8985C5	w_{13} = 8CFAAB96	w_{14} = 734B7483	w_{15} = 2475A2B3
4	47AB5B7D	w_{16} = B822deb8	w_{17} = 34D8752E	w_{18} = 479301AD	w_{19} = 54010FFA
5	6C762D20	w_{20} = D454F398	w_{21} = E08C86B6	w_{22} = A71F871B	w_{23} = F31E88E1
6	52C4F80D	w_{24} = 86900B95	w_{25} = 661C8D23	w_{26} = C1030A38	w_{27} = 321D82D9
7	E4133523	w_{28} = 62833EB6	w_{29} = 049FB395	w_{30} = C59CB9AD	w_{31} = F7813B74
8	8CE29268	w_{32} = EE61ACDE	w_{33} = EAFE1F4B	w_{34} = 2F62A6E6	w_{35} = D8E39D92
9	0A5E4F61	w_{36} = E43FE3BF	w_{37} = 0EC1FCF4	w_{38} = 21A35A12	w_{39} = F940C780
10	3FC6CD99	w_{40} = DBF92E26	w_{41} = D538D2D2	w_{42} = F49B88C0	w_{43} = 0DDB4F40



Key Expansion

Table 7.5 shows how the keys for each round are calculated assuming that the 128-bit cipher key agreed upon by Alice and Bob is (24 75 A2 B3 34 75 56 88 31 E2 12 00 13 AA 54 87)$_{16}$.

Table 7.5 *Key expansion example*

Round	*Values of t's*	*First word in the round*	*Second word in the round*	*Third word in the round*	*Fourth word in the round*
—		w_{00} = 2475A2B3	w_{01} = 34755688	w_{02} = 31E21200	w_{03} = 13AA5487
1	AD20177D	w_{04} = 8955B5CE	w_{05} = BD20E346	w_{06} = 8CC2F146	w_{07} = 9F68A5C1
2	470678DB	w_{08} = CE53CD15	w_{09} = 73732E53	w_{10} = FFB1DF15	w_{11} = 60D97AD4
3	31DA48D0	w_{12} = FF8985C5	w_{13} = 8CFAAB96	w_{14} = 734B7483	w_{15} = 2475A2B3
4	47AB5B7D	w_{16} = B822deb8	w_{17} = 34D8752E	w_{18} = 479301AD	w_{19} = 54010FFA
5	6C762D20	w_{20} = D454F398	w_{21} = E08C86B6	w_{22} = A71F871B	w_{23} = F31E88E1
6	52C4F80D	w_{24} = 86900B95	w_{25} = 661C8D23	w_{26} = C1030A38	w_{27} = 321D82D9
7	E4133523	w_{28} = 62833EB6	w_{29} = 049FB395	w_{30} = C59CB9AD	w_{31} = F7813B74
8	8CE29268	w_{32} = EE61ACDE	w_{33} = EAFE1F4B	w_{34} = 2F62A6E6	w_{35} = D8E39D92
9	0A5E4F61	w_{36} = E43FE3BF	w_{37} = 0EC1FCF4	w_{38} = 21A35A12	w_{39} = F940C780
10	3FC6CD99	w_{40} = DBF92E26	w_{41} = D538D2D2	w_{42} = F49B88C0	w_{43} = 0DDB4F40

Round	*Constant (RCon)*	*Round*	*Constant (RCon)*
1	(**01** 00 00 00)$_{16}$	6	(**20** 00 00 00)$_{16}$
2	(**02** 00 00 00)$_{16}$	7	(**40** 00 00 00)$_{16}$
3	(**04** 00 00 00)$_{16}$	8	(**80** 00 00 00)$_{16}$
4	(**08** 00 00 00)$_{16}$	9	(**1B** 00 00 00)$_{16}$
5	(**10** 00 00 00)$_{16}$	10	(**36** 00 00 00)$_{16}$

$t_i = \text{subword}(\text{Rotword}(w_{i-1})) \oplus \text{Rcon}_{i/4}$

$t_4 = \text{subword}(\text{Rotword}(w_{4-1})) \oplus \text{Rcon}_{4/4}$

$t_4 = \text{subword}(\text{Rotword}(w_3)) \oplus \text{Rcon}_1$

Rotword(13AA5487) = AA548713

Subword (AA548713) = AC20177D

t_4 = AC20177D $\oplus$ Rcon $_1$

= AC20177D $\oplus$ **01 00 00 00 ➔ AD20177D**

Key Expansion –AES 192 and AES 256

Key-expansion algorithms in the AES-192 and AES-256 versions are very similar to the key expansion algorithm in AES-128, with the following differences:

1. In AES-192, the words are generated in groups of six instead of four.
   a. The cipher key creates the first six words (w_0 to w_5).
   b. If $i \bmod 6 \neq 0$, $w_i \leftarrow w_{i-1} + w_{i-6}$; otherwise, $w_i \leftarrow t + w_{i-6}$.
2. In AES-256, the words are generated in groups of eight instead of four.
   a. The cipher key creates the first eight words (w_0 to w_7).
   b. If $i \bmod 8 \neq 0$, $w_i \leftarrow w_{i-1} + w_{i-8}$; otherwise, $w_i \leftarrow t + w_{i-8}$.
   c. If $i \bmod 4 = 0$, but $i \bmod 8 \neq 0$, then $w_i = \text{SubWord}(w_{i-1}) + w_{i-8}$.

Key expansion analysis

The key-expansion mechanism in AES has been designed to provide several features that thwart the cryptanalyst.

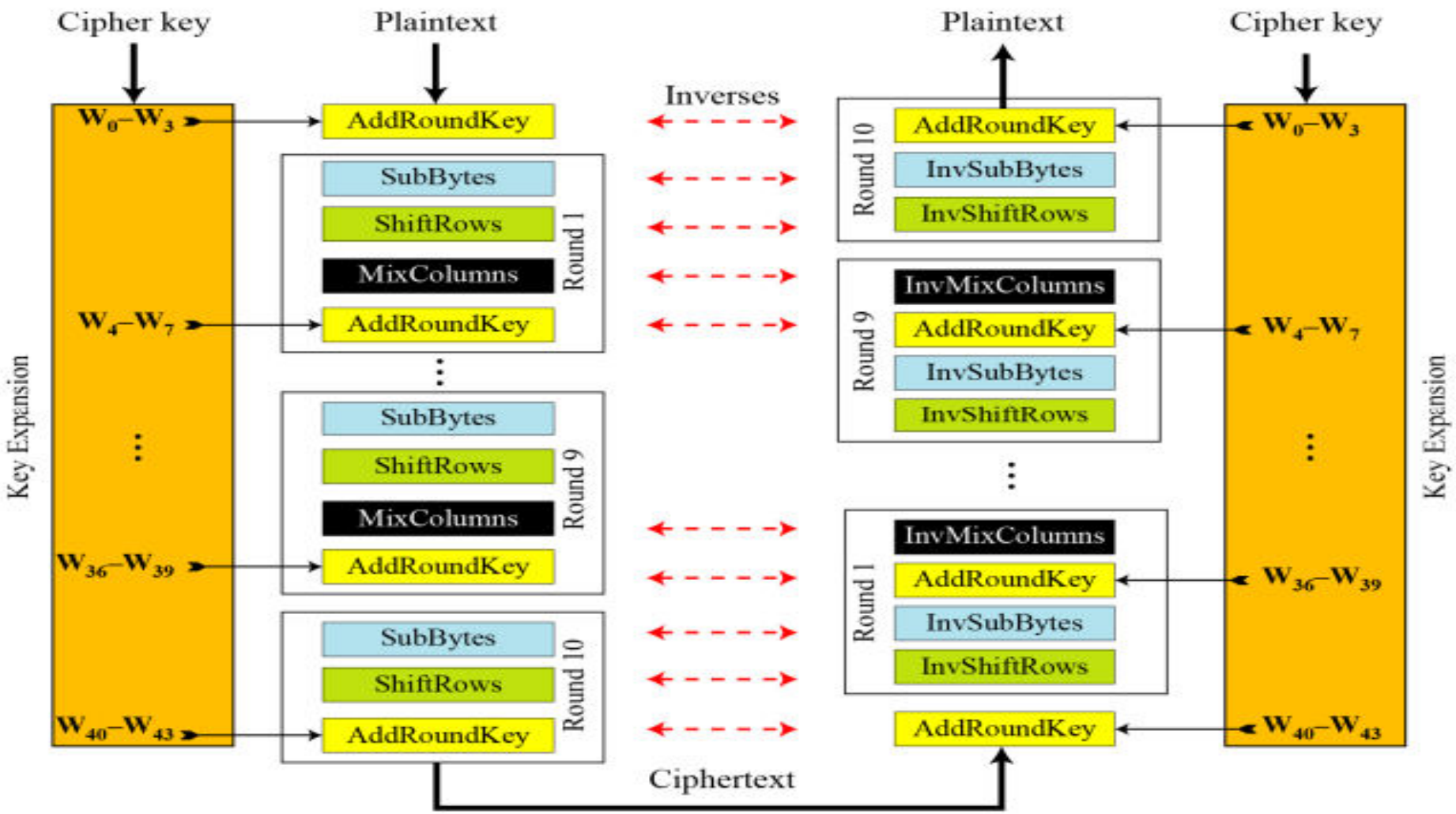
1. Even if Eve knows only part of the cipher key or the values of the words in some round keys, she still needs to find the rest of the cipher key before she can find all round keys. This is because of the nonlinearity produced by SubWord transformation in the key-expansion process.
2. Two different cipher keys, no matter how similar to each other, produce two expansions that differ in at least a few rounds.
3. Each bit of the cipher key is diffused into several rounds. For example, changing a single bit in the cipher key, will change some bits in several rounds.
4. The use of the constants, the RCons, removes any symmetry that may have been created by the other transformations.
5. There are no serious weak keys in AES, unlike in DES.
6. The key-expansion process can be easily implemented on all platforms.
7. The key-expansion routine can be implemented without storing a single table; all calculations can be done using the $GF(2^8)$ and FG(2) fields.

The AES Ciphers

- AES uses four types of transformations for encryption and decryption.
- Encryption algorithm is referred to as the cipher
- Decryption algorithm as the inverse cipher.
- Two different design for implementation
  - Original Design
  - Alternative Design

RAMAIAH
Institute of Technology

The AES Ciphers – Original design



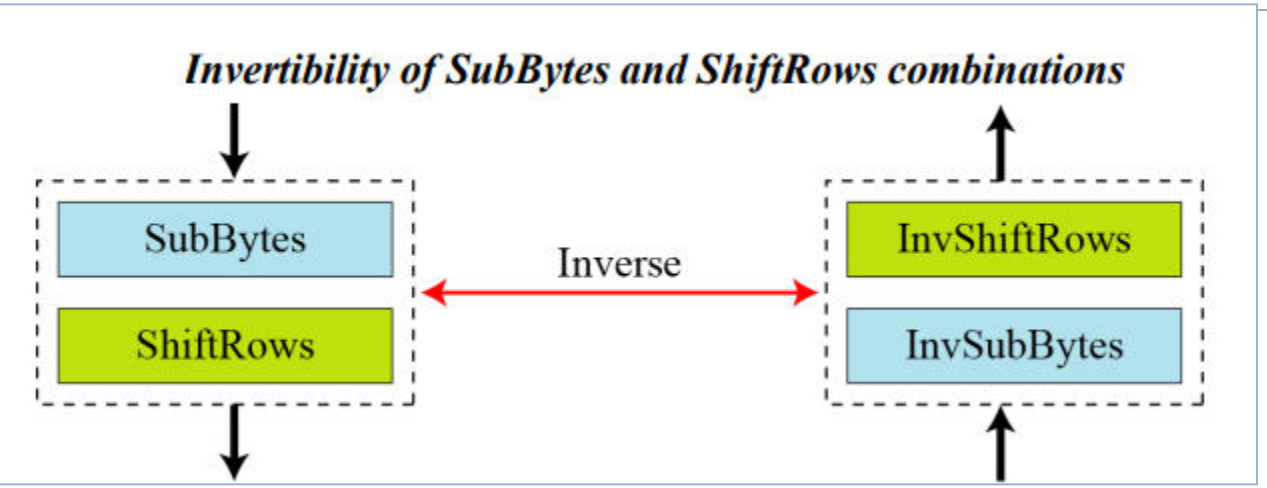
The AES Ciphers –Original design

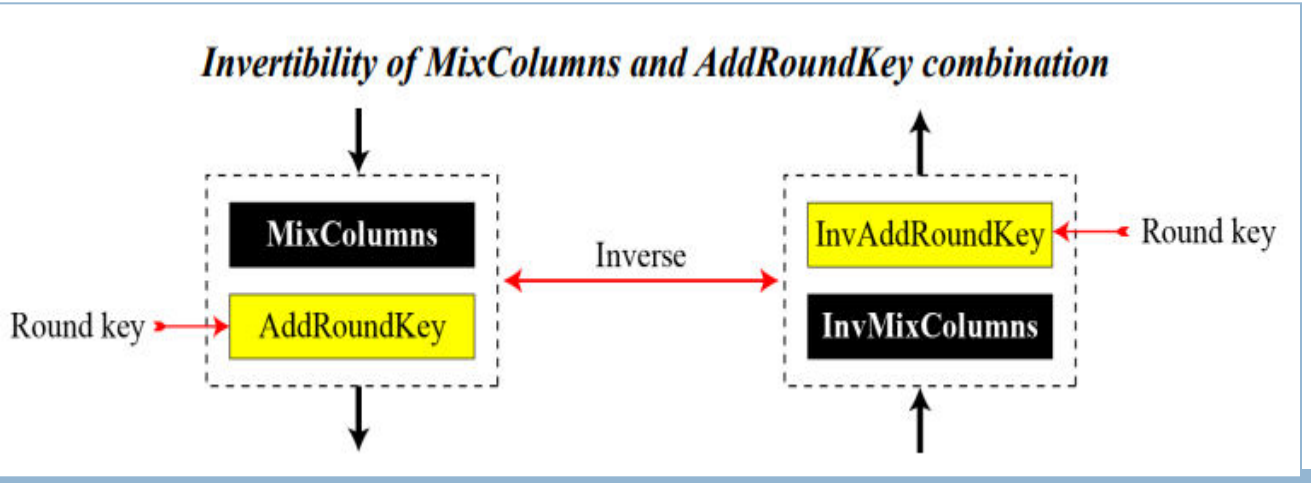
The code for the AES-128 version of this design is shown in Algorithm

Pseudocode for cipher in the original design

```
Cipher (InBlock [16], OutBlock[16], w[0 … 43])
{
    BlockToState (InBlock, S)

    S ← AddRoundKey (S, w[0…3])
     for (round = 1 to 10)
     {
         S ← SubBytes (S)
         S ← ShiftRows (S)
          if (round ≠ 10)  S ← MixColumns (S)
          S ← AddRoundKey (S, w[4 × round, 4 × round + 3])
     }

    StateToBlock (S, OutBlock);
}
```

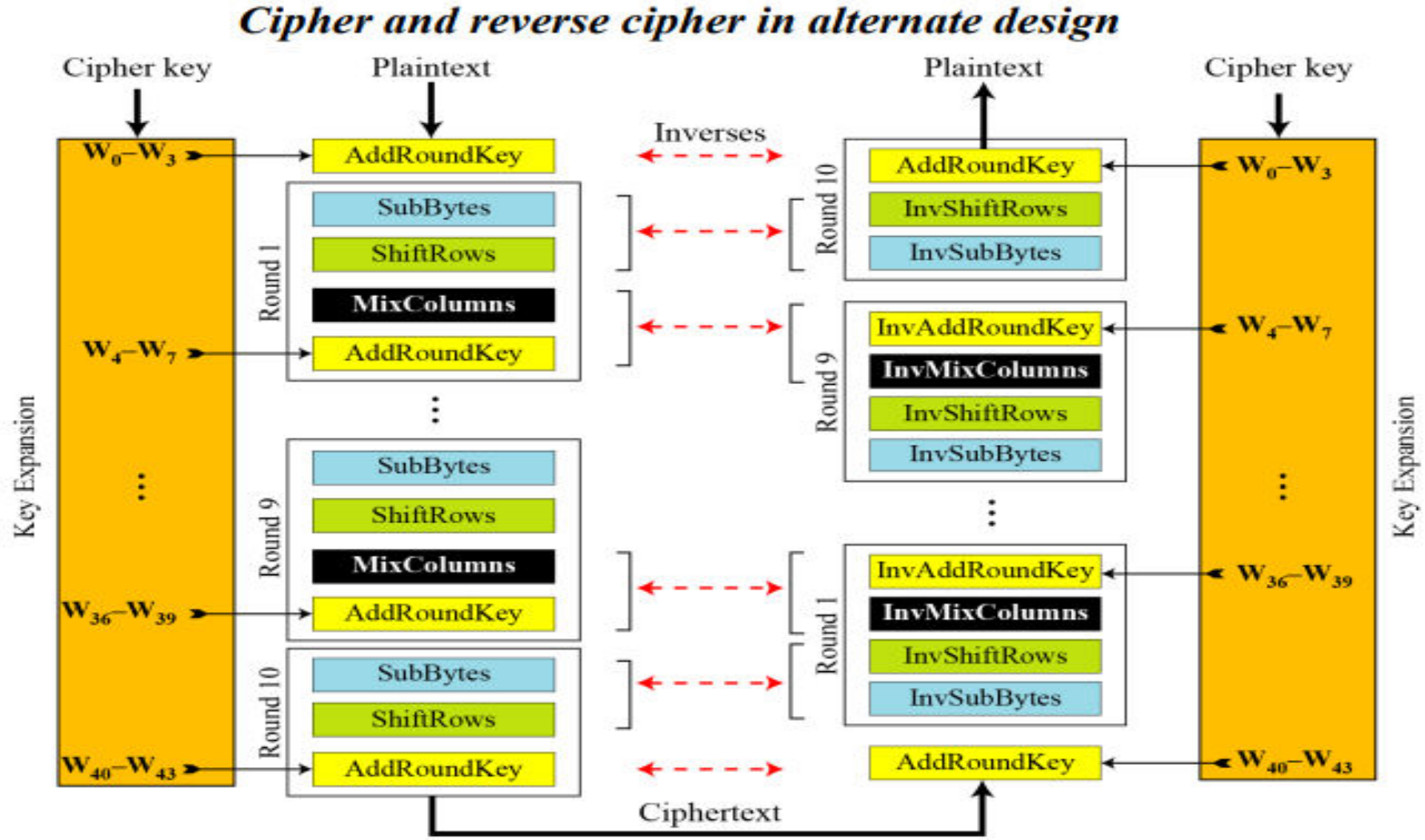
The AES Ciphers –Alternative Design

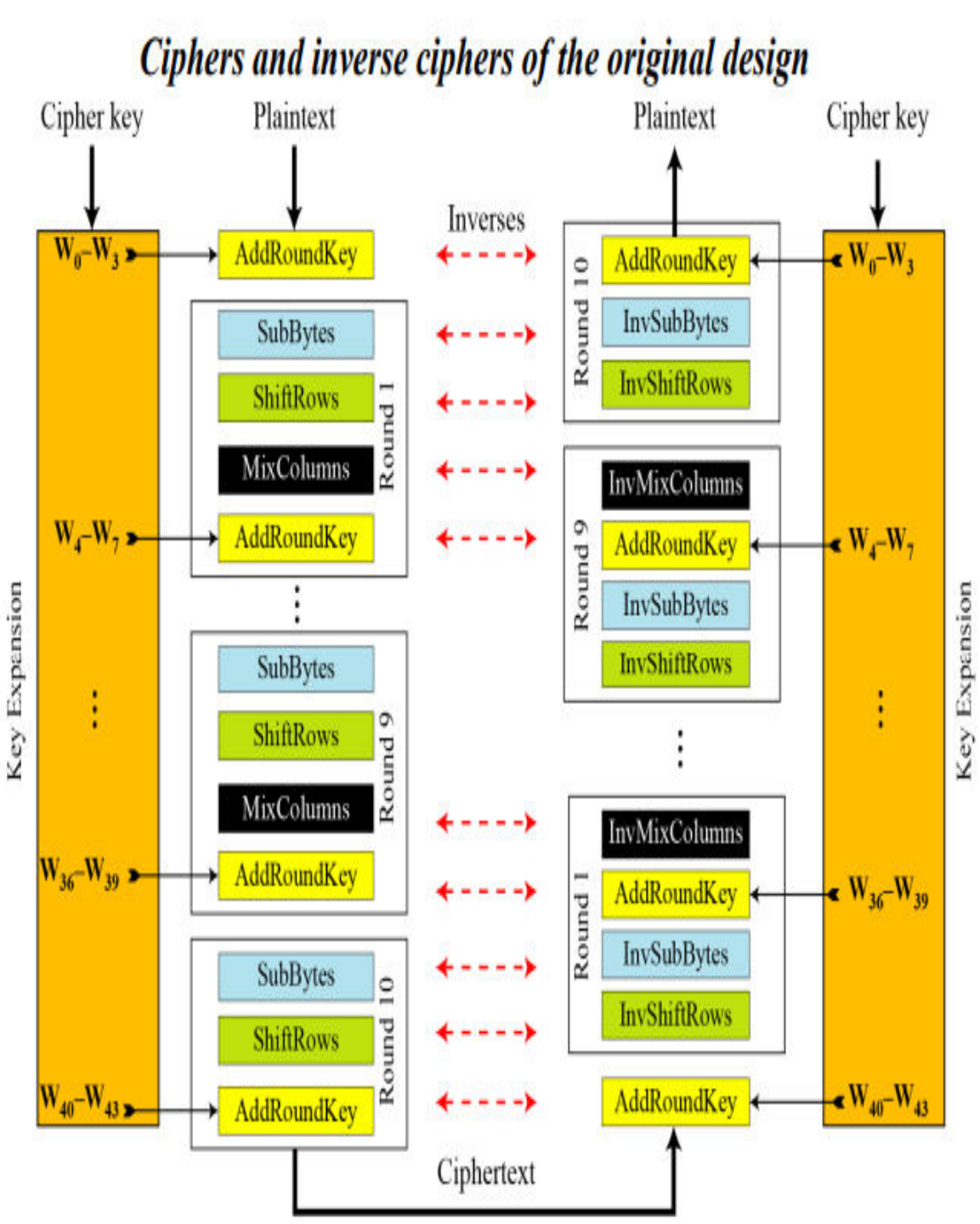


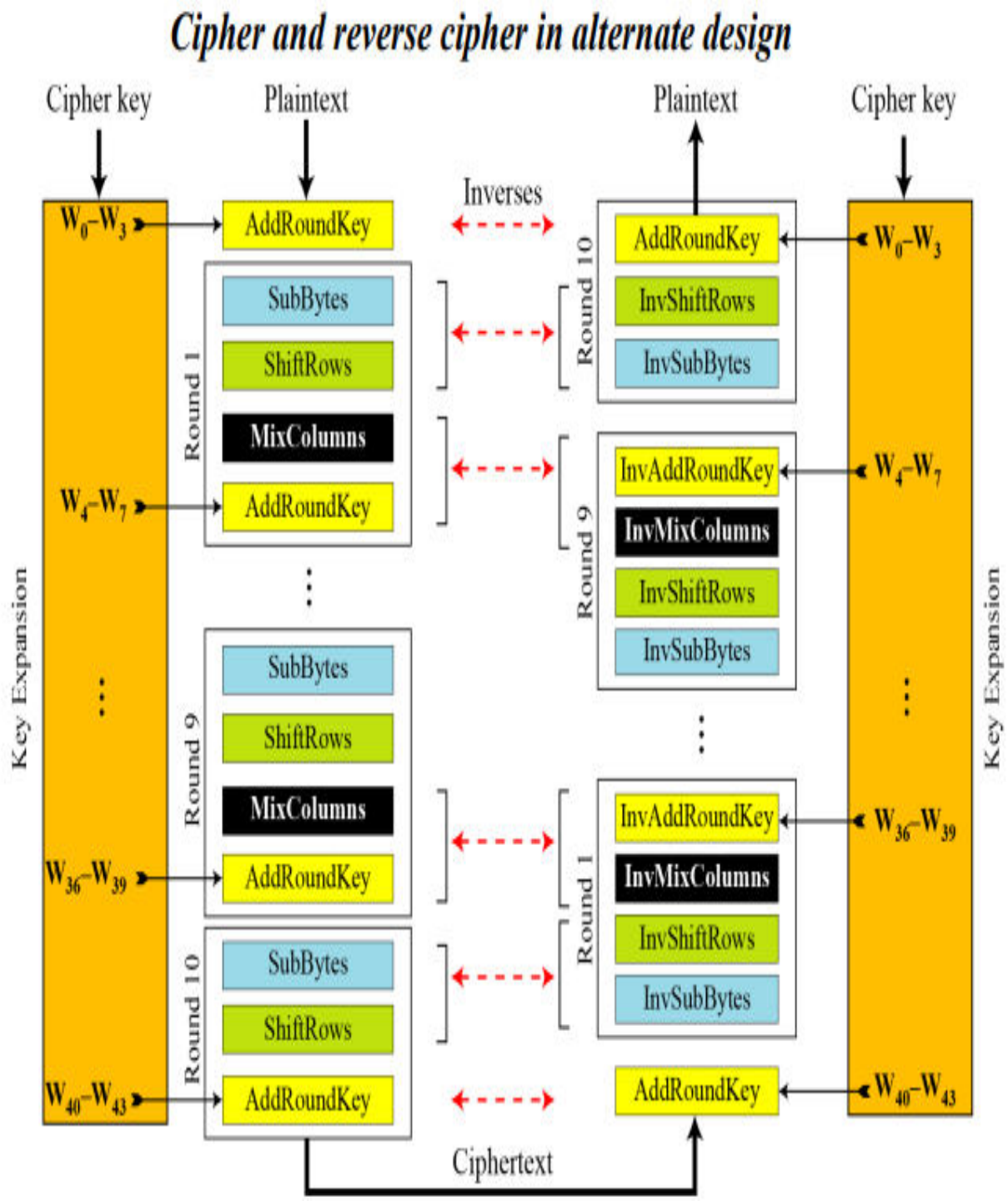


RAMAIAH
Institute of Technology

The AES Ciphers –Alternative Design




Ciphers and inverse ciphers of the original design
Cipher key
Plaintext
Plaintext
Cipher key
Inverses
Key Expansion
Key Expansion
W0–W3
W4–W7
W36–W39
W40–W43
AddRoundKey
SubBytes
ShiftRows
MixColumns
Round 1
Round 9
Round 10
InvSubBytes
InvShiftRows
InvMixColumns
Ciphertext


Cipher and reverse cipher in alternate design
Cipher key
Plaintext
Plaintext
Cipher key
Inverses
Key Expansion
Key Expansion
W0–W3
W4–W7
W36–W39
W40–W43
AddRoundKey
SubBytes
ShiftRows
MixColumns
Round 1
Round 9
Round 10
InvAddRoundKey
InvMixColumns
InvShiftRows
InvSubBytes
Ciphertext

Analysis of AES

This section is a brief review of the three characteristics of AES.

- Security
- Implementation
- Simplicity and Cost

Analysis of AES

Security

- Brute-Force Attack :AES is definitely more secure than DES due to the larger-size key.
- Statistical Attacks :Numerous tests have failed to do statistical analysis of the ciphertext.
- Differential and Linear Attacks :There are no differential and linear attacks on AES as yet.

Analysis of AES

Implementation

AES can be implemented in software, hardware, and firmware.

The implementation can use table lookup process or routines that use a well-defined algebraic structure.

Analysis of AES

Simplicity and Cost

The algorithms used in AES are so simple that they can be easily implemented using cheap processors and a minimum amount of memory.

THANK YOU