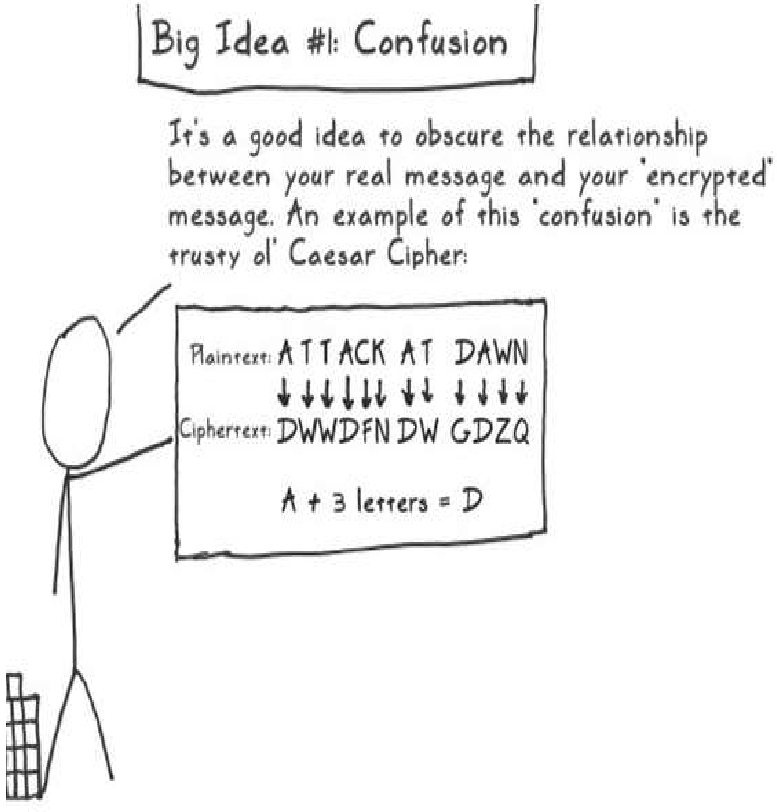
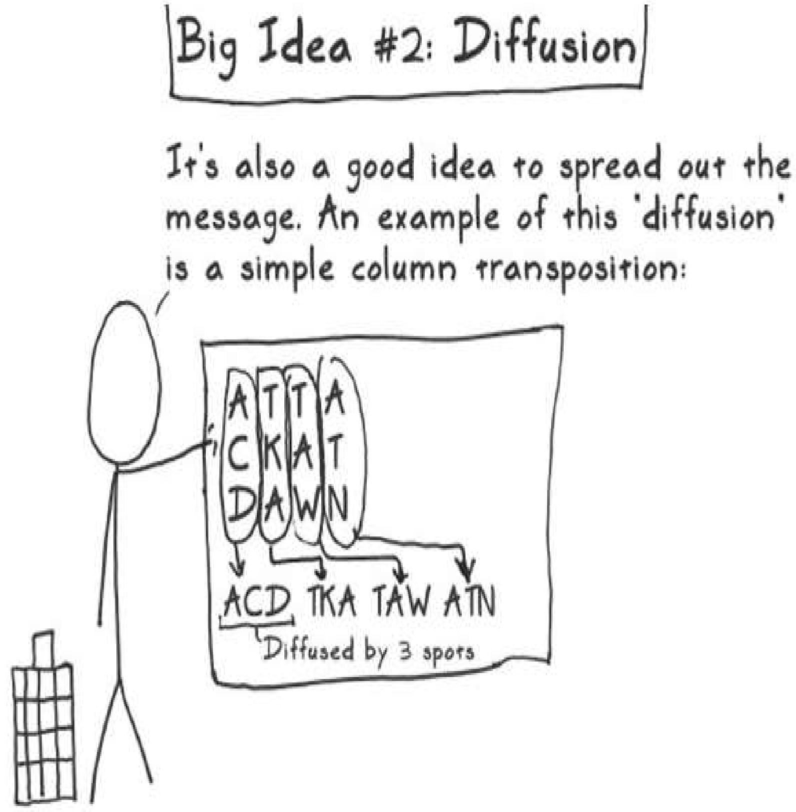
MODULE II

- IDEA: Primitive operations- Key expansions- One round, Odd round, Even Round- Inverse keys for decryption. AES: Basic Structure- Primitive operation- Inverse Cipher- Key Expansion, Rounds, Inverse Rounds. Stream Cipher –RC4.

- Cryptography (i.e., Confusion and Diffusion)





IDEA

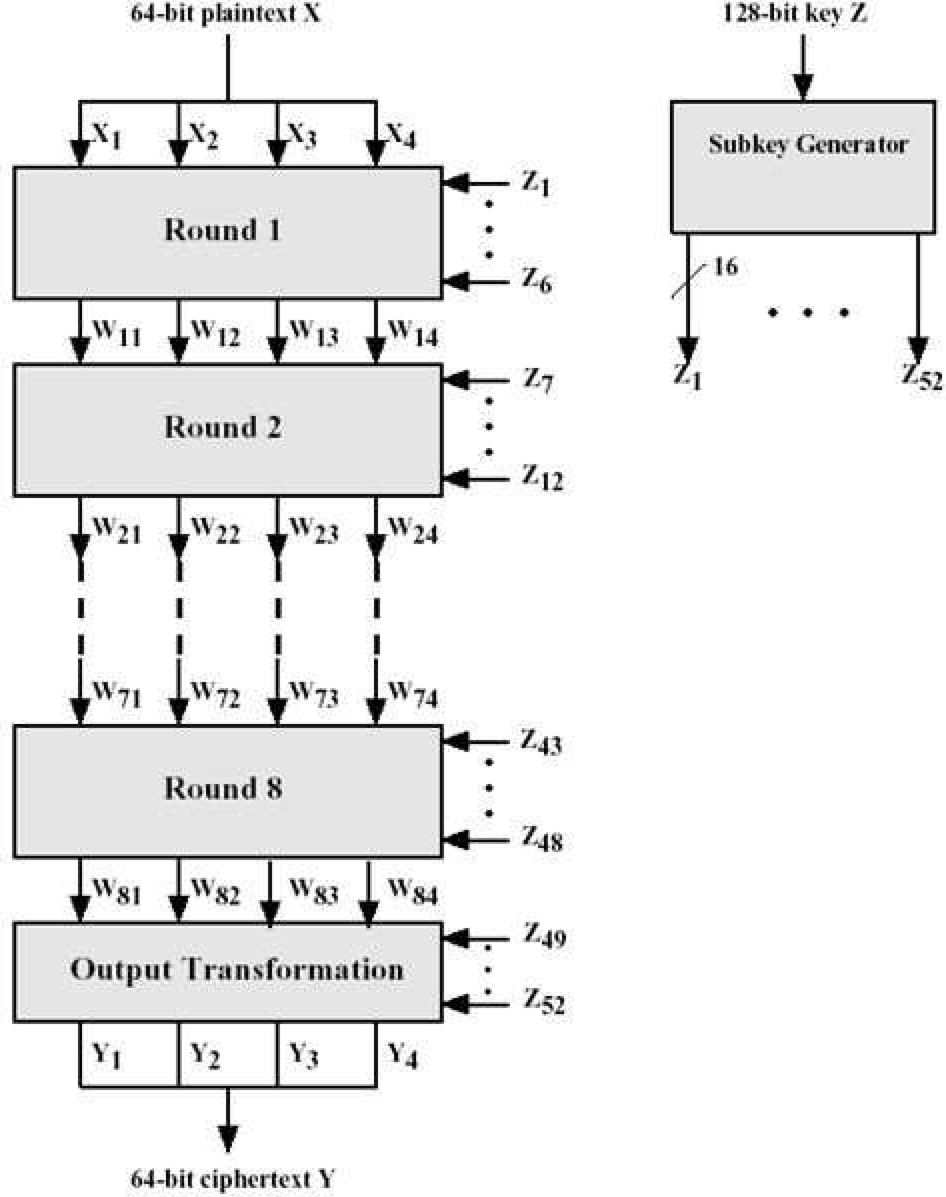
- International Data Encryption Algorithm
- Symmetric block cipher
- 128 bit key
- Encrypt data in blocks of 64 bits

Cryptographic Strength

- Block Length
- Key Length
- Confusion
- Diffusion

IDEA Encryption

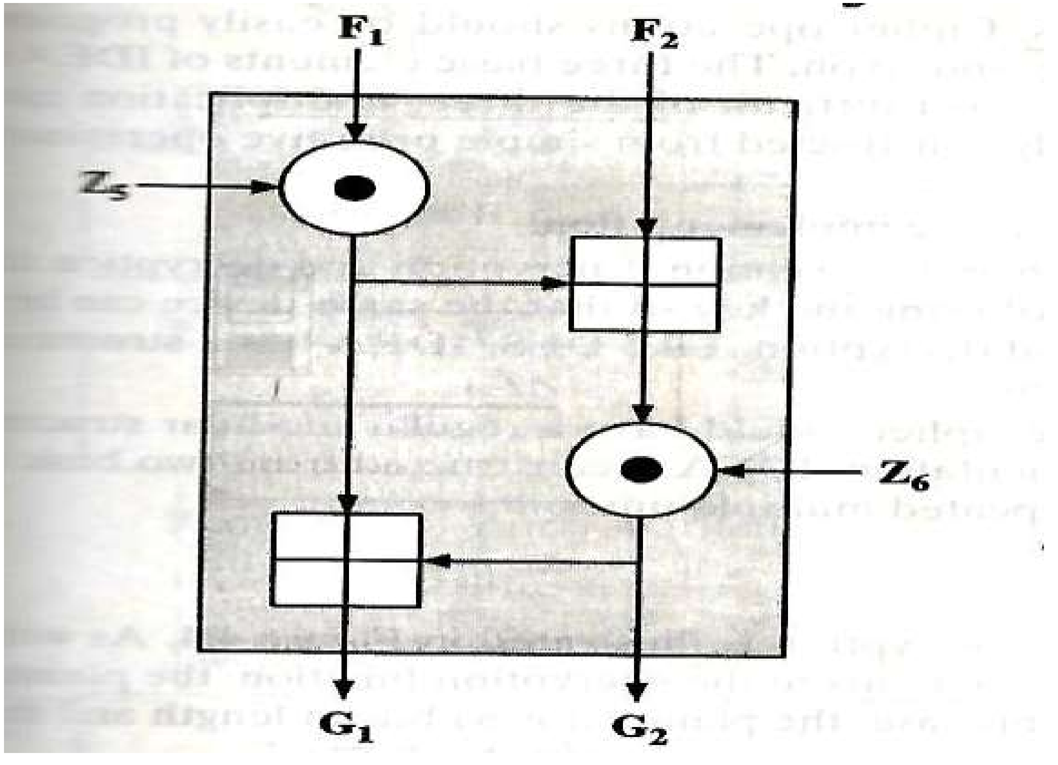
- plaintext – 64 bits
- Key – 128 bits
- 8 rounds followed by a final transformation function
- Each of the rounds makes use of six 16 bit subkeys, where as the final transformation uses four subkeys, for a total of 52 sub keys


64-bit plaintext X
128-bit key Z
X1
X2
X3
X4
Subkey Generator
Round 1
Z1
Z6
16
W11
W12
W13
W14
Z1
Z52
Round 2
Z7
Z12
W21
W22
W23
W24
W71
W72
W73
W74
Round 8
Z43
Z48
W81
W82
W83
W84
Output Transformation
Z49
Z52
Y1
Y2
Y3
Y4
64-bit ciphertext Y

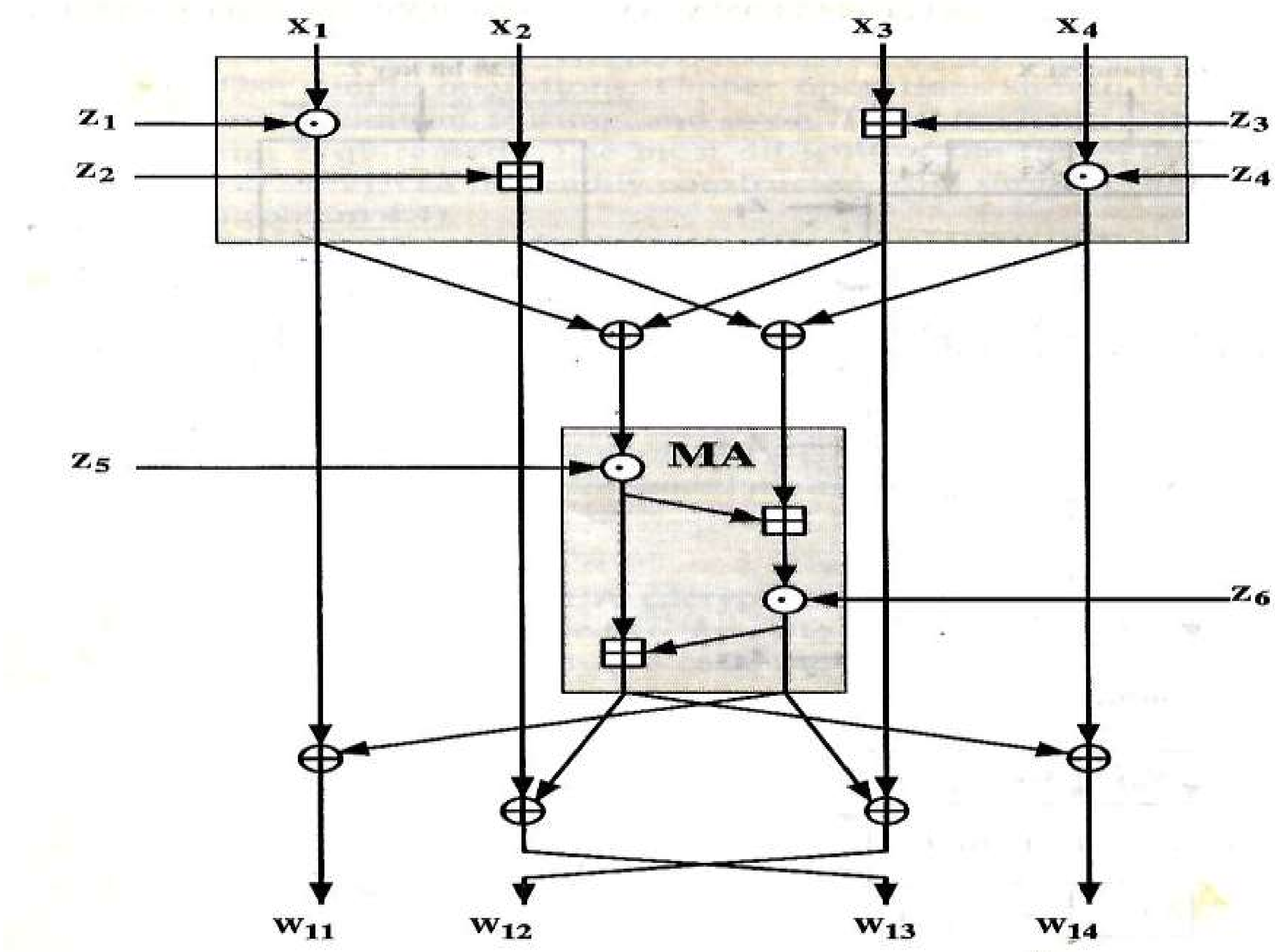
Diffusion

- Provided by the basic building block of algorithm known as Multiplication Addition Structure.
- Takes as inputs two 16 bit values derived from plaintext & two 16 bit subkeys derived from the key.
- Produces two 16-bit outputs
- This structure is repeated 8 times in algorithm
- Provides very effective diffusion

Multiplication Addition (MA) Structure



Details of a Single Round- Odd Round



Details of a Single Round- Odd Round (1)

- Round begins with a transformation
- That combines four input subblocks with four subkeys
- Using the addition & multiplication operations
- Four output blocks produce by this transformation are then combined using the XOR operation to form two 16 bit blocks that are input to the MA structure.

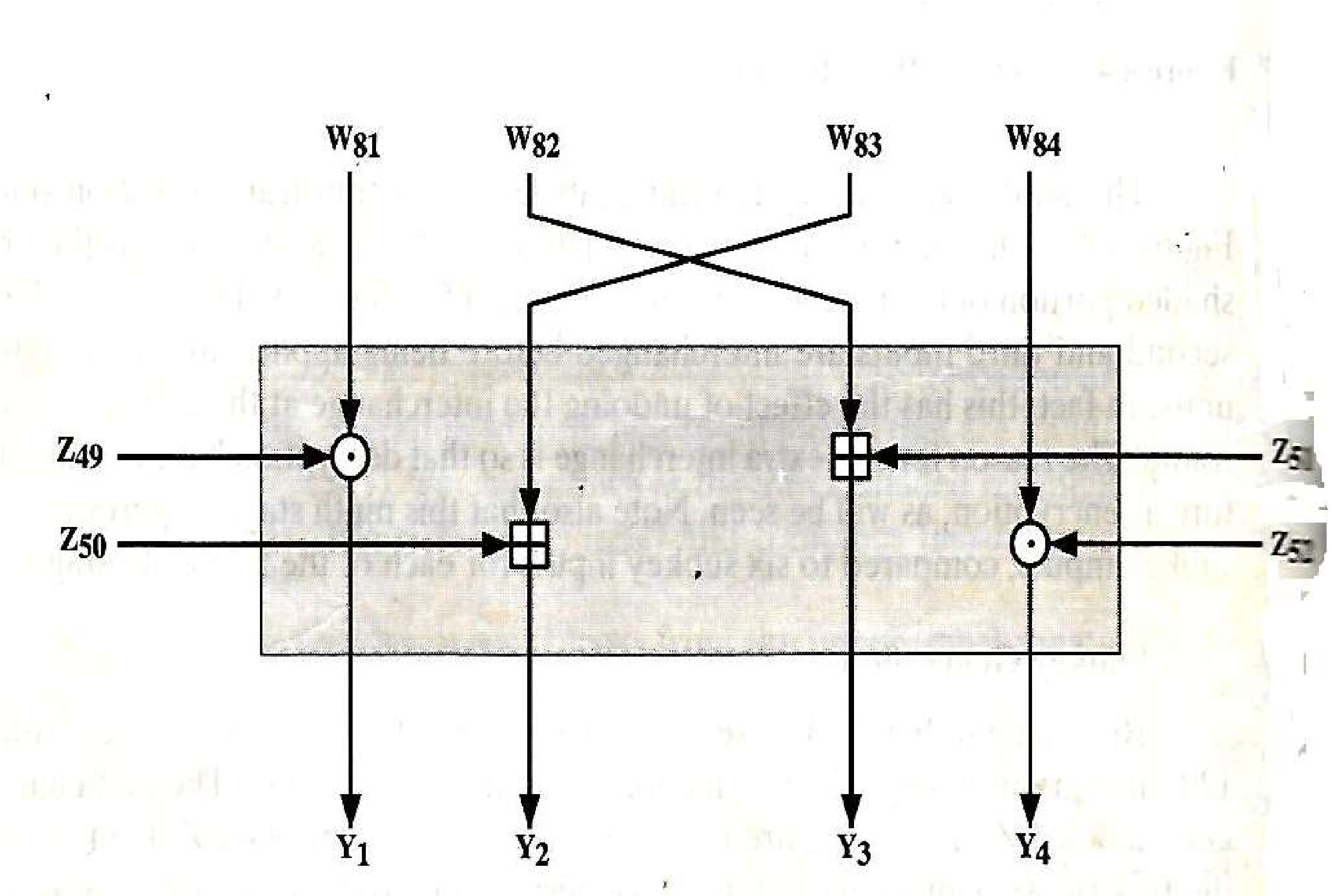
Details of a Single Round- Odd Round (2)

- MA structure also takes two subkeys as input
- Combines these inputs to produce two 16-bit outputs
- Finally the 4 output blocks from the upper transformation are combined with the two output blocks of MA structure using XOR to produce the 4 output blocks for this round.
- Second & third inputs are interchanged to produce the second & third output (w_{12} & w_{13})

Even Round

- Subsequent rounds have the same structure but with different subkey & plaintext derived inputs

Ninth stage – output Transformation Stage



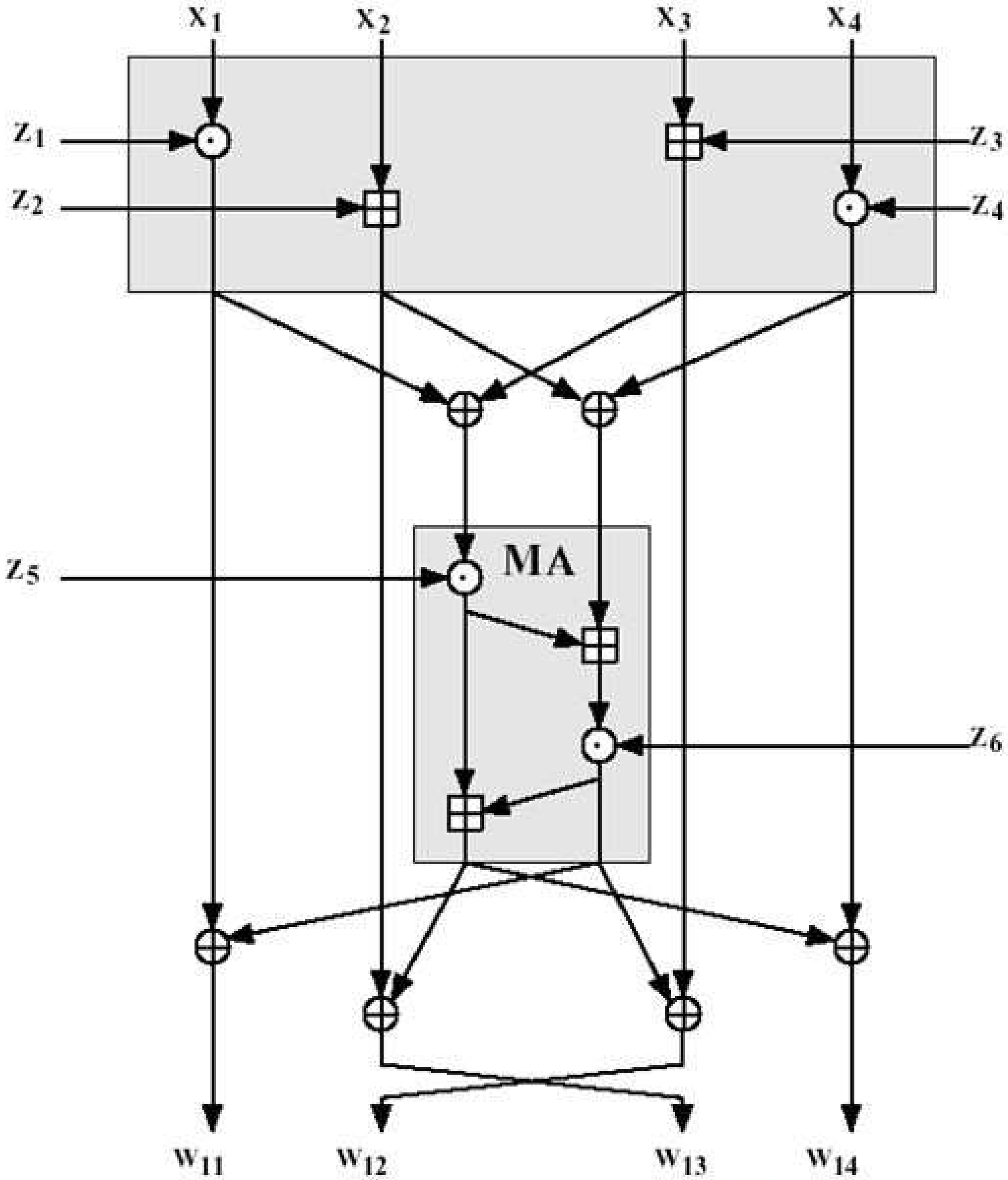
Ninth stage – output Transformation Stage

- Second & third inputs are interchanged before being applied to the operational units

Subkey Generation

- 52, 16 bit subkeys are generated from 128-bit encryption key
- First eight subkeys, labeled $Z_1, Z_2, \ldots\ldots\ldots, Z_8$ are taken directly from the key
- Z_1 being equal to the first 16 bits
- Z_2 being equal to the next 16 bits
- Then a circular left shift of 25 bit positions is applied to the key & the next 8 subkeys are extracted
- This procedure is repeated untill all 52 subkeys are generated.

Single Round of IDEA (1st Round)



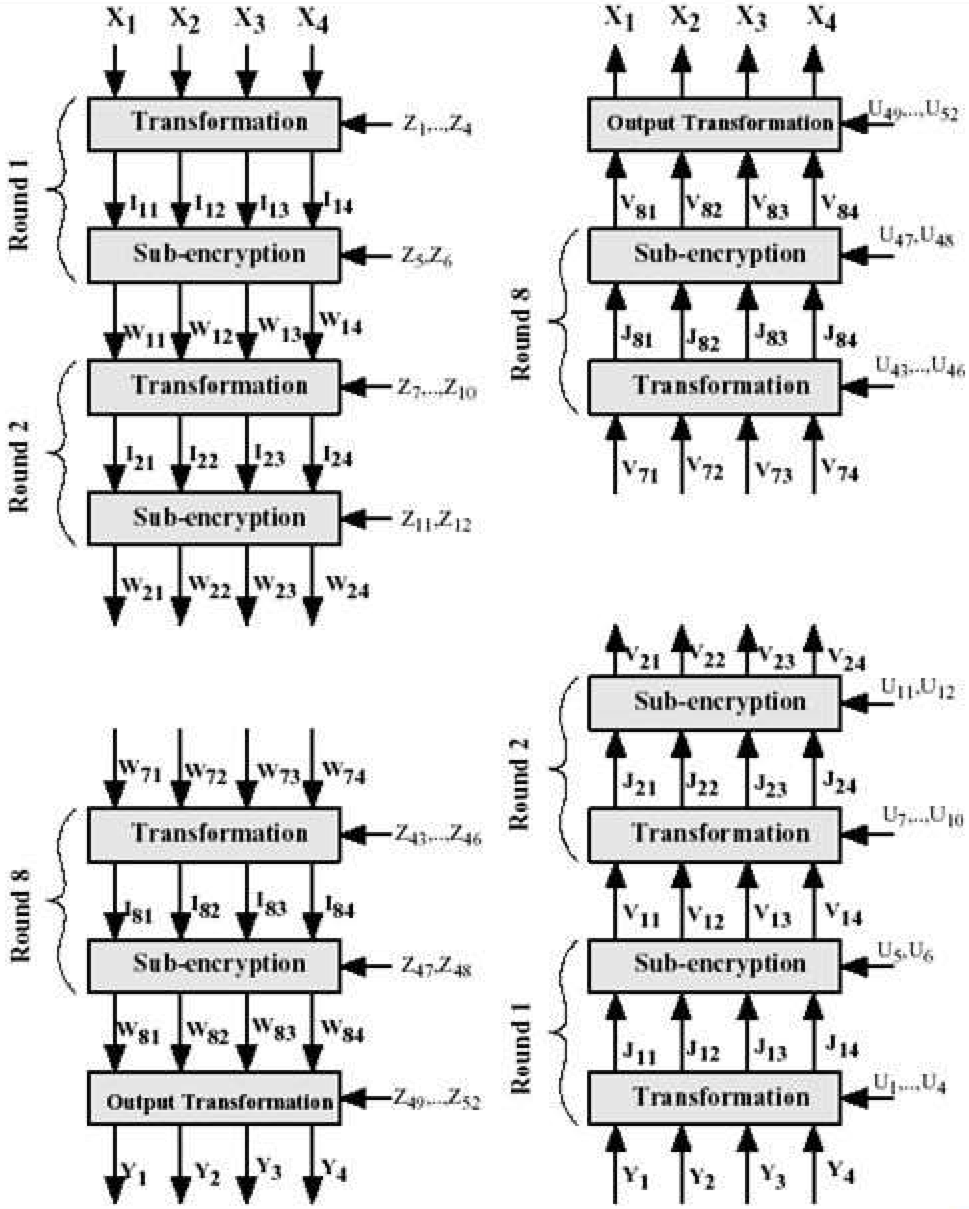
Transformation

Sub-encryption

Table2 for encryption sub key

Round 1	Z_1	Z_2	Z_3	Z_4	Z_5	Z_6	Z_7	Z_8	Z_9	Z_{10}	Z_{11}	Z_{12}
Round 2	Z_{13}	Z_{14}	Z_{15}	Z_{16}	Z_{17}	Z_{18}	Z_{19}	Z_{20}	Z_{21}	Z_{22}	Z_{23}	Z_{24}
Round 3	Z_{25}	Z_{26}	Z_{27}	Z_{28}	Z_{29}	Z_{30}	Z_{31}	Z_{32}	Z_{33}	Z_{34}	Z_{35}	Z_{36}
Round 4	Z_{37}	Z_{38}	Z_{39}	Z_{40}	Z_{41}	Z_{42}	Z_{43}	Z_{44}	Z_{45}	Z_{46}	Z_{47}	Z_{48}
Round 5	Z_{49}	Z_{50}	Z_{51}	Z_{52}	Z_{53}	Z_{54}	Z_{55}	Z_{56}	Z_{57}	Z_{58}	Z_{59}	Z_{60}
Round 6	Z_{61}	Z_{62}	Z_{63}	Z_{64}	Z_{65}	Z_{66}	Z_{67}	Z_{68}	Z_{69}	Z_{70}	Z_{71}	Z_{72}
Round 7	Z_{73}	Z_{74}	Z_{75}	Z_{76}	Z_{77}	Z_{78}	Z_{79}	Z_{80}	Z_{81}	Z_{82}	Z_{83}	Z_{84}
Round 8	Z_{85}	Z_{86}	Z_{87}	Z_{88}	Z_{89}	Z_{90}	Z_{91}	Z_{92}	Z_{93}	Z_{94}	Z_{95}	Z_{96}
Round 9	Z_{97}	Z_{98}	Z_{99}	Z_{100}	Z_{101}	Z_{102}	Z_{103}	Z_{104}				

IDEA Decryption



- Use the same structure (algorithm) as the encryption, but with different subkeys
- Decryption subkeys $U_1, \ldots, U_{52}$ are derived from encryption subkeys

AES

- Advanced Encryption Standard (AES)
- **designed by Rijndael**
- symmetric block cipher.
- plaintext block size of 128 bits, or 16 bytes.
- Key length can be 16, 24, or32 bytes (128, 192, or 256 bits)
- The algorithm is referred to as AES-128, AES-192, orAES-256, depending on the key length.

AES

- Input to the encryption and decryption algorithms is a single 128-bit block.
- This block is depicted as a 4 * 4 square matrix of bytes.
- This block is copied into the **State array, which is modified at each stage of encryption or decryption.**
- After the final stage, **State is copied to an output matrix.**

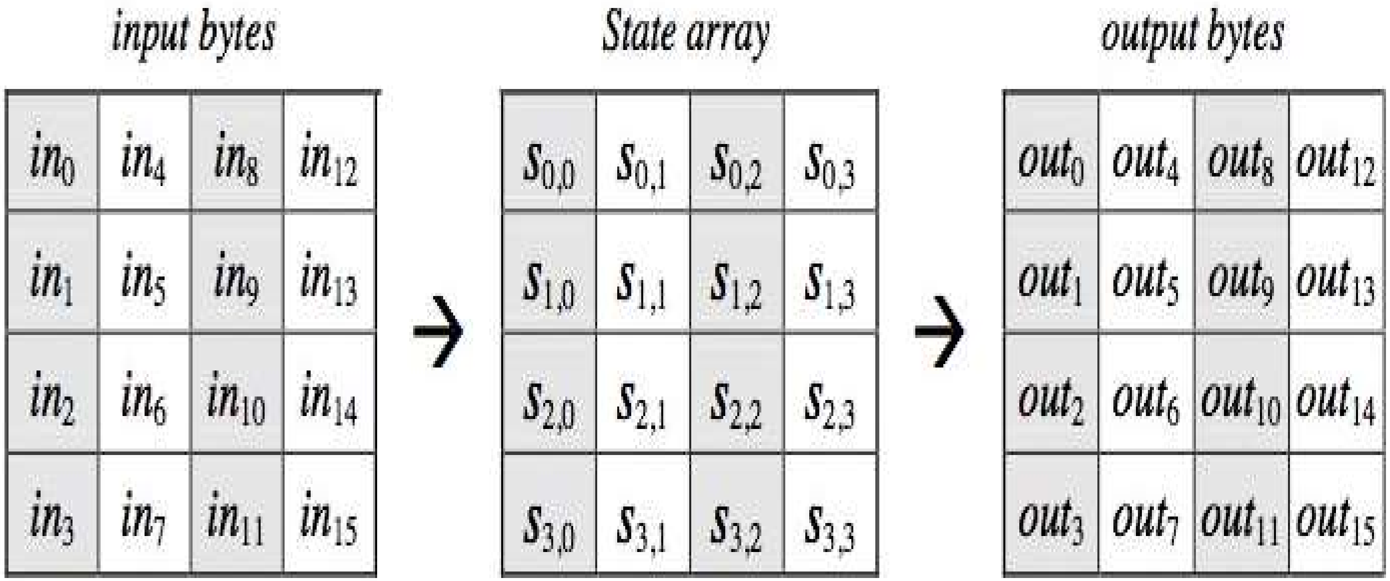
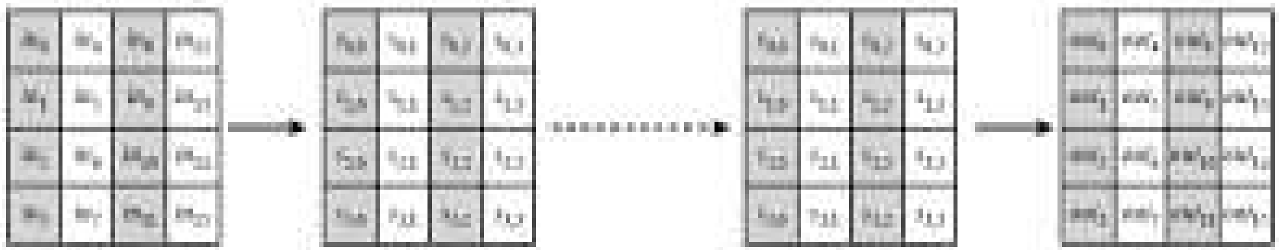


Figure 3. State array input and output.



(a) Input, state array, and output

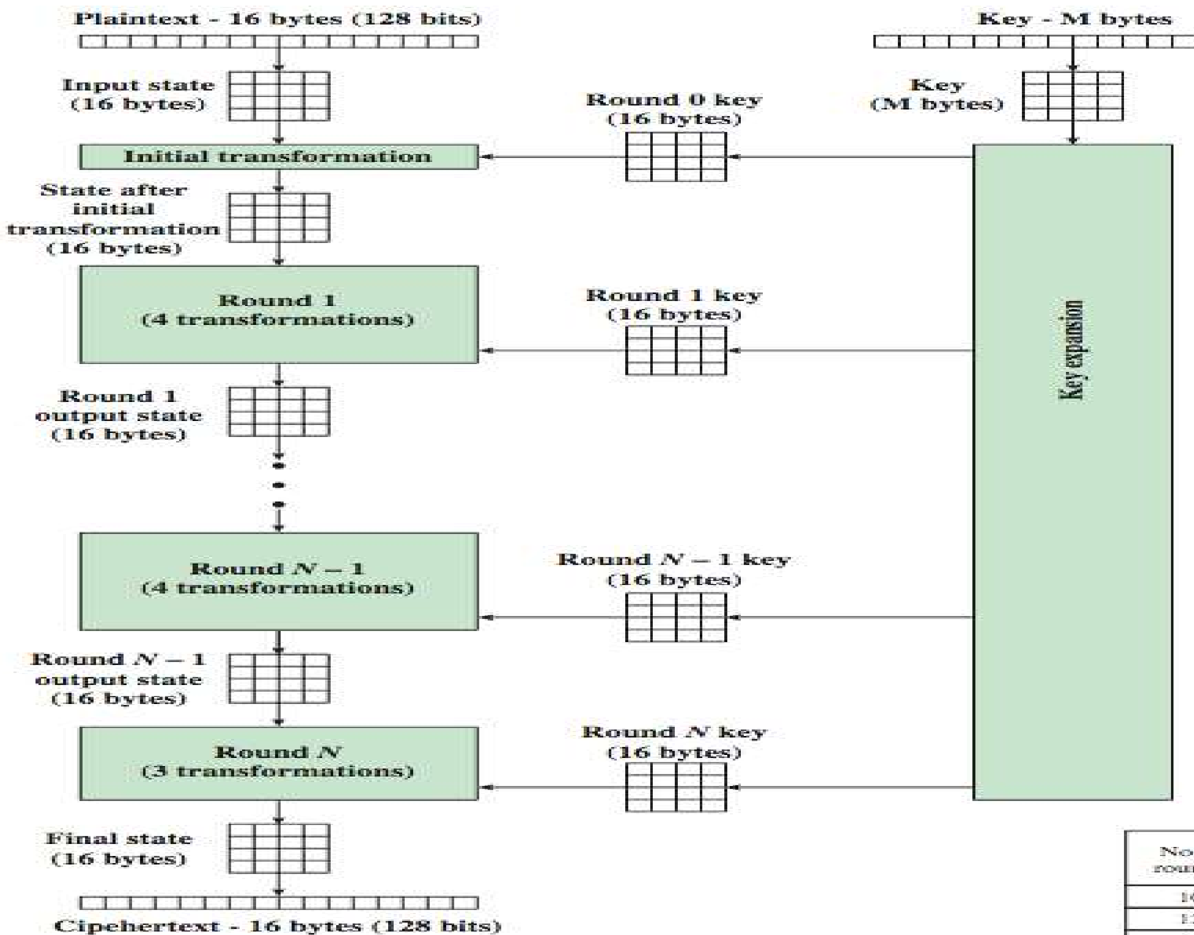
(b) Key and expanded key

Key & Expanded Key

- Similarly, the key is depicted as a square matrix of bytes.
- key is then expanded into an array of key schedule words.
- Each word is four bytes, and the total key schedule is 44 words for the 128-bit key.

- The ordering of bytes within a matrix is by column.
- So, for example, the first four bytes of a 128-bit plaintext input to the encryption cipher occupy the first column of the in matrix,
- the second four bytes occupy the second column, and so on.

AES Encryption Process

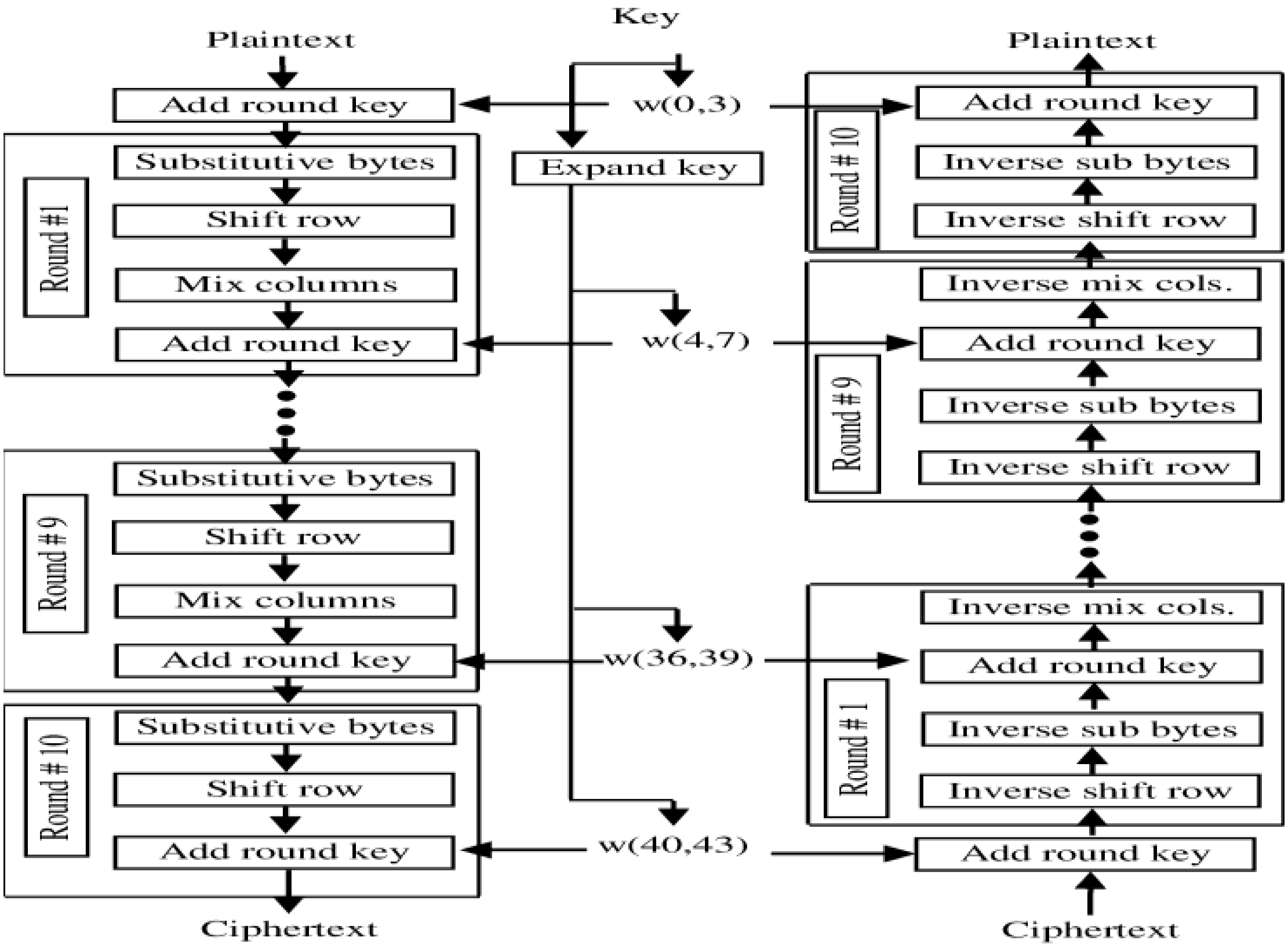


No.of rounds	Key Length (bytes)
10	16
12	24
14	32

The first N - 1 rounds consist of four distinct transformation functions:

- **SubBytes**
- **ShiftRows**
- **MixColumns**
- **AddRoundKey**
- The final round contains only three transformations
- Initial single transformation (AddRoundKey) before the first round, which can be considered as Round 0.

Encryption & Decryption



Overall AES structure (1)

- This structure is not a Feistel structure.
- In the classic Feistel structure, half of the data block is used to modify the other half of the data block and then the halves are swapped.
- AES instead processes the entire data block as a single matrix during each round using substitutions and permutation.

Overall AES structure (2)

- The key that is provided as input is expanded into an array of forty-four 32-bit words, w[i].
- Four distinct words (128 bits) serve as a round key for each round.
- Four different stages are used, one of permutation and three of substitution:

Overall AES structure (3)

- **Substitute bytes:** Uses an S-box to perform a byte-by-byte substitution of the block
- **ShiftRows:** A simple permutation
- **MixColumns:** A substitution that makes use of arithmetic over GF(28)
- **AddRoundKey:** A simple bitwise XOR of the current block with a portion of the expanded key.

Overall AES structure (3)

- The structure is quite simple.
- For both encryption and decryption, the cipher begins with an AddRoundKey stage, followed by nine rounds that each includes all four stages, followed by a tenth round of three stages.

Overall AES structure (3)

- Only the AddRoundKey stage makes use of the key.
- For this reason, the cipher begins and ends with an AddRoundKey stage.
- Any other stage, applied at the beginning or end, is reversible without knowledge of the key and so would add no security.

Overall AES structure (3)

- The AddRoundKey stage is, in effect, a form of Vernam cipher and by itself would not be formidable.
- The other three stages together provide confusion,diffusion, and nonlinearity, but by themselves would provide no security because they do not use the key.

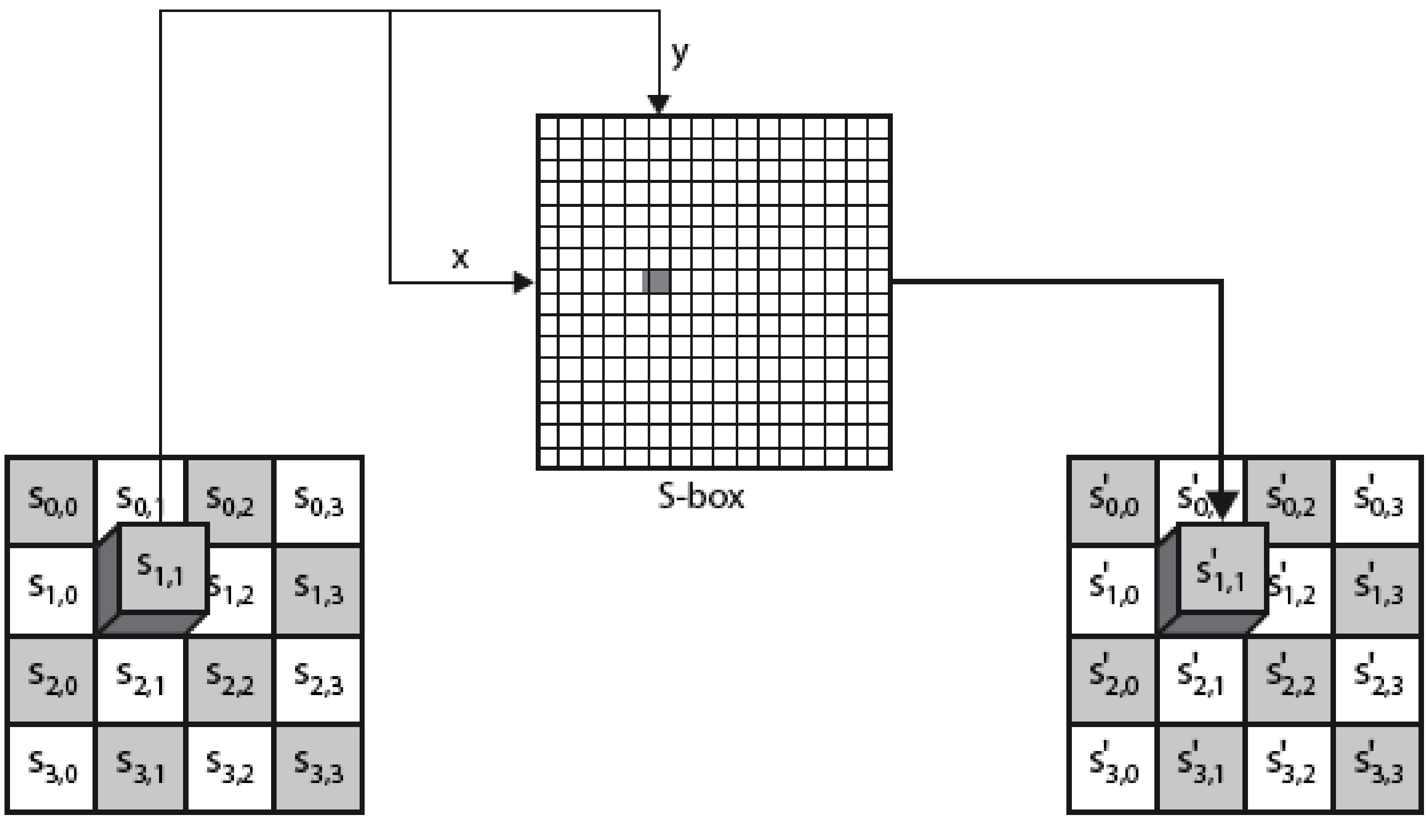
AES: PRIMITIVE OPERATIONS

- **Substitute Bytes Transformation**
- **Forward and Inverse Transformations**
- The **forward substitute byte transformation, called SubBytes, is a simple**
- table lookup as shown in Figure below.

Substitute Bytes

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

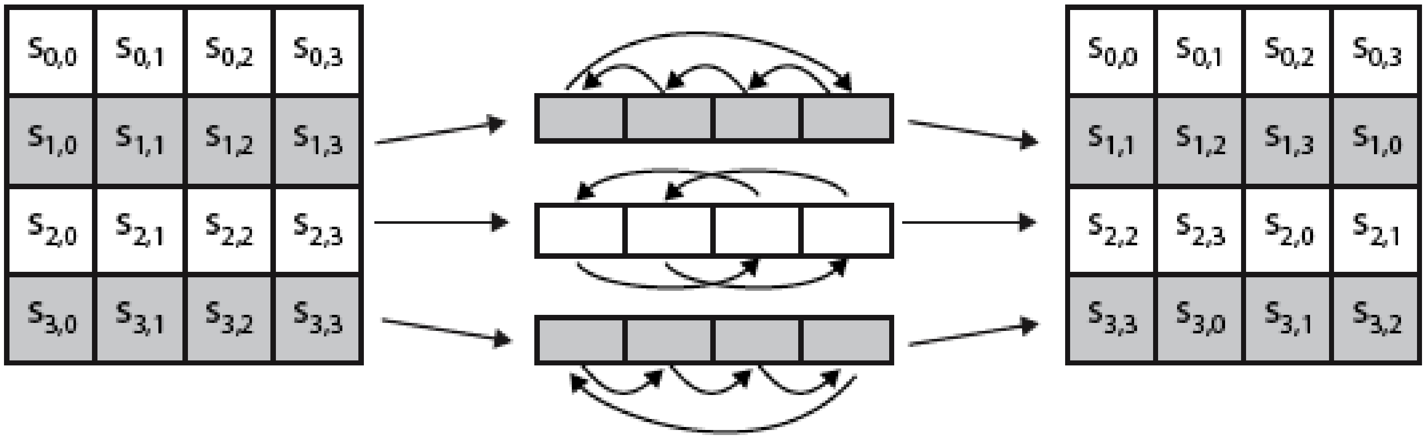
Substitute Bytes



Shift Rows

- a circular byte shift in each
  - 1st row is unchanged
  - 2nd row does 1 byte circular shift to left
  - 3rd row does 2 byte circular shift to left
  - 4th row does 3 byte circular shift to left
- decrypt inverts using shifts to right
- since state is processed by columns, this step permutes bytes between the columns

Shift Rows



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

→

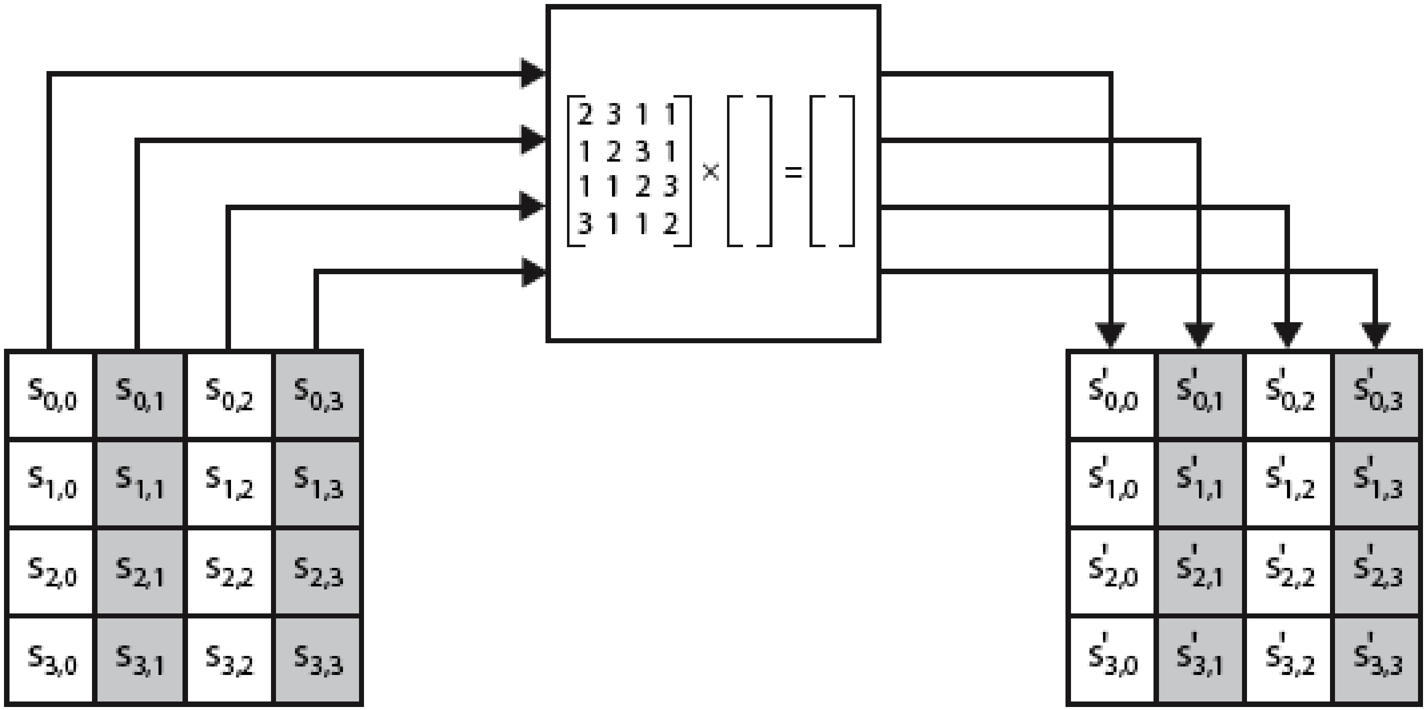
87	F2	4D	97
6E	4C	90	EC
46	E7	4A	C3
A6	8C	D8	95

Mix Columns

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

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

Mix Columns

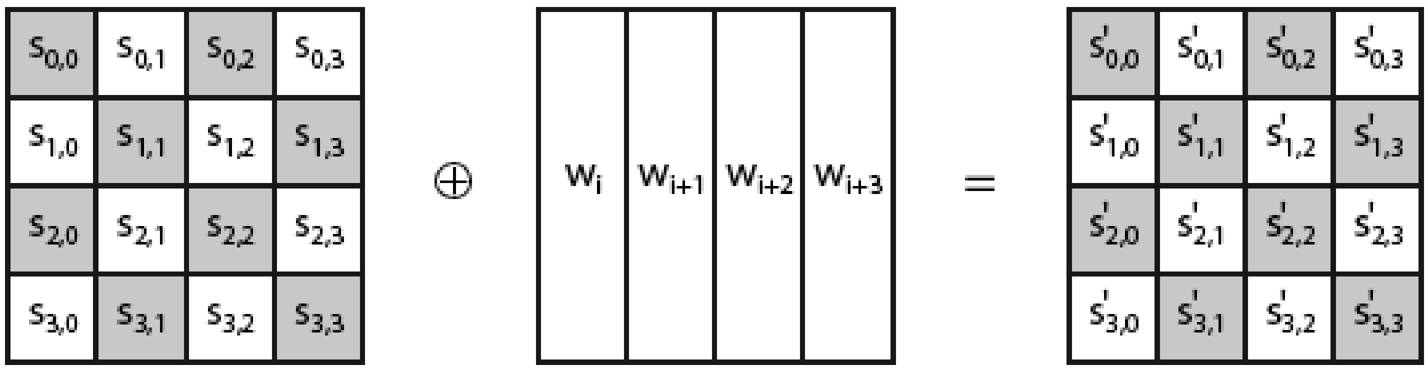


$s_{0,0}$ $s_{0,1}$ $s_{0,2}$ $s_{0,3}$
$s_{1,0}$ $s_{1,1}$ $s_{1,2}$ $s_{1,3}$
$s_{2,0}$ $s_{2,1}$ $s_{2,2}$ $s_{2,3}$
$s_{3,0}$ $s_{3,1}$ $s_{3,2}$ $s_{3,3}$
$\begin{bmatrix} 2 & 3 & 1 & 1 \\ 1 & 2 & 3 & 1 \\ 1 & 1 & 2 & 3 \\ 3 & 1 & 1 & 2 \end{bmatrix} \times \begin{bmatrix} \\ \end{bmatrix} = \begin{bmatrix}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

Add Round Key

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

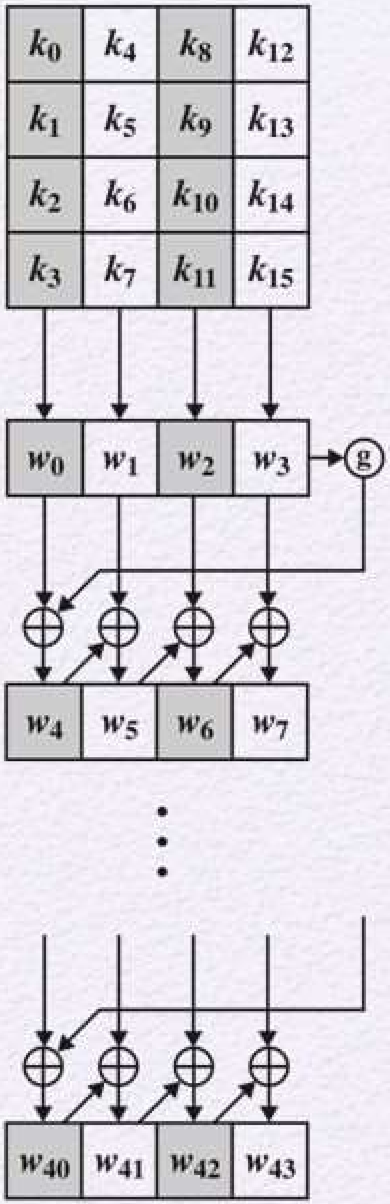
Add Round Key



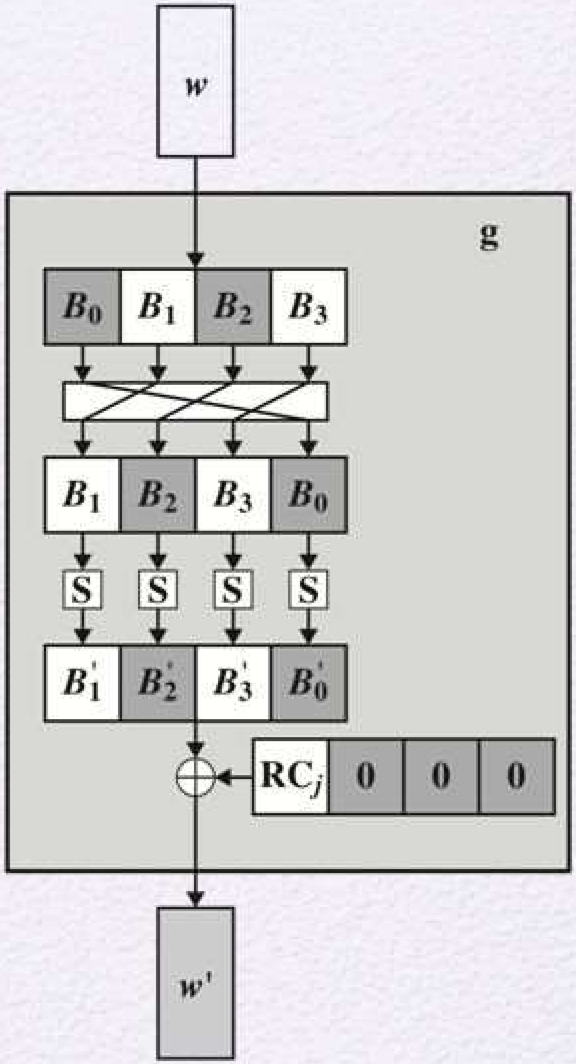
AES:Key Expansion

- AES key expansion algorithm takes as input a four-word (16-byte) key & produces a linear array of 44 words (176 bytes)
- The key is copied into the first four words of the expanded key.
- Remainder of the expanded key is filled in four words at a time.
- Each added word w[i]depends on the immediately preceding word, w[i - 1]

AES Key Expansion



(a) Overall algorithm



(b) Function g

Figure 5.9 AES Key Expansion

Function g

1. RotWord performs a one-byte circular left shift on a word. This means that an input word [B0, B1, B2, B3] is transformed into [B1, B2, B3, B0].
2. SubWord performs a byte substitution on each byte of its input word, using the S-box.
3. The result of steps 1 and 2 is XORed with a round constant, Rcon[j].

- **The round** constant is a word in which the three right most bytes are always 0.
- Thus, the effect of an XOR of a word with Rcon is to only perform an XOR on the leftmost byte of the word.

Encryption Round

- An encryption round has the structure

  SubBytes

  ShiftRows

  MixColumns

  AddRoundKey.

Decryption Round

- **InvShiftRows**
- **InvSubBytes**
- **AddRoundKey**
- **InvMixColumns**
- Thus, the first two stages of the decryption rounds need to be interchanged, and the second two stages of the decryption rounds need to be interchanged.

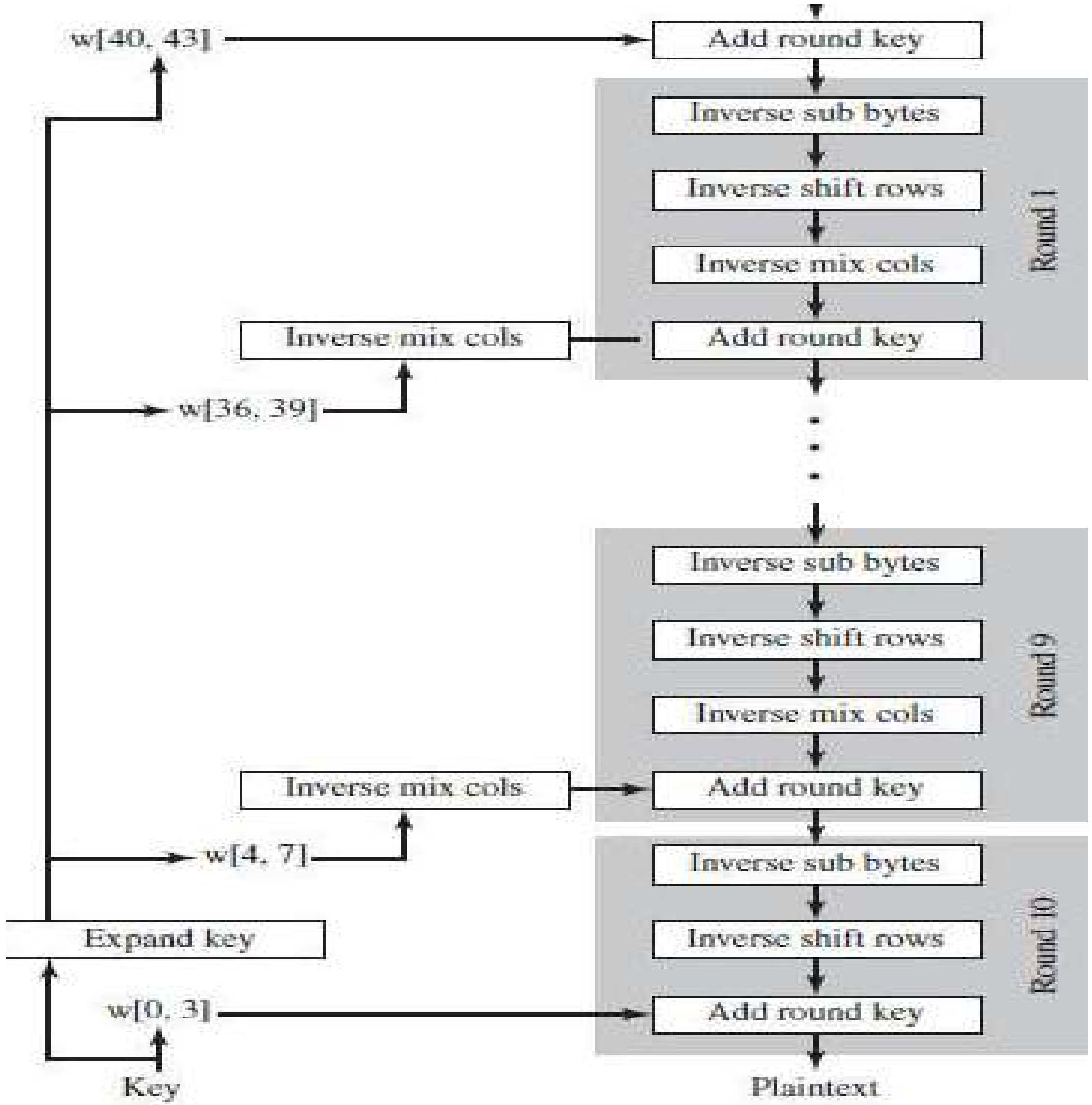
Interchanging InvShift Rows and InvSubBytes

- InvShiftRows affects the sequence of bytes in **State but does not alter byte** contents and does not depend on byte contents to perform its transformation.
- For a given **State Si,**

  InvShiftRows [InvSubBytes (Si)] = InvSubBytes [InvShiftRows (Si)]

Interchanging AddRoundKey and InvMixColumns

- The transformations AddRoundKey and InvMixColumns do not alter the sequence of bytes in **State.**
- **If the key can be viewed as a sequence of words, then** both AddRoundKey and InvMixColumns operate on **State one column at a time.**

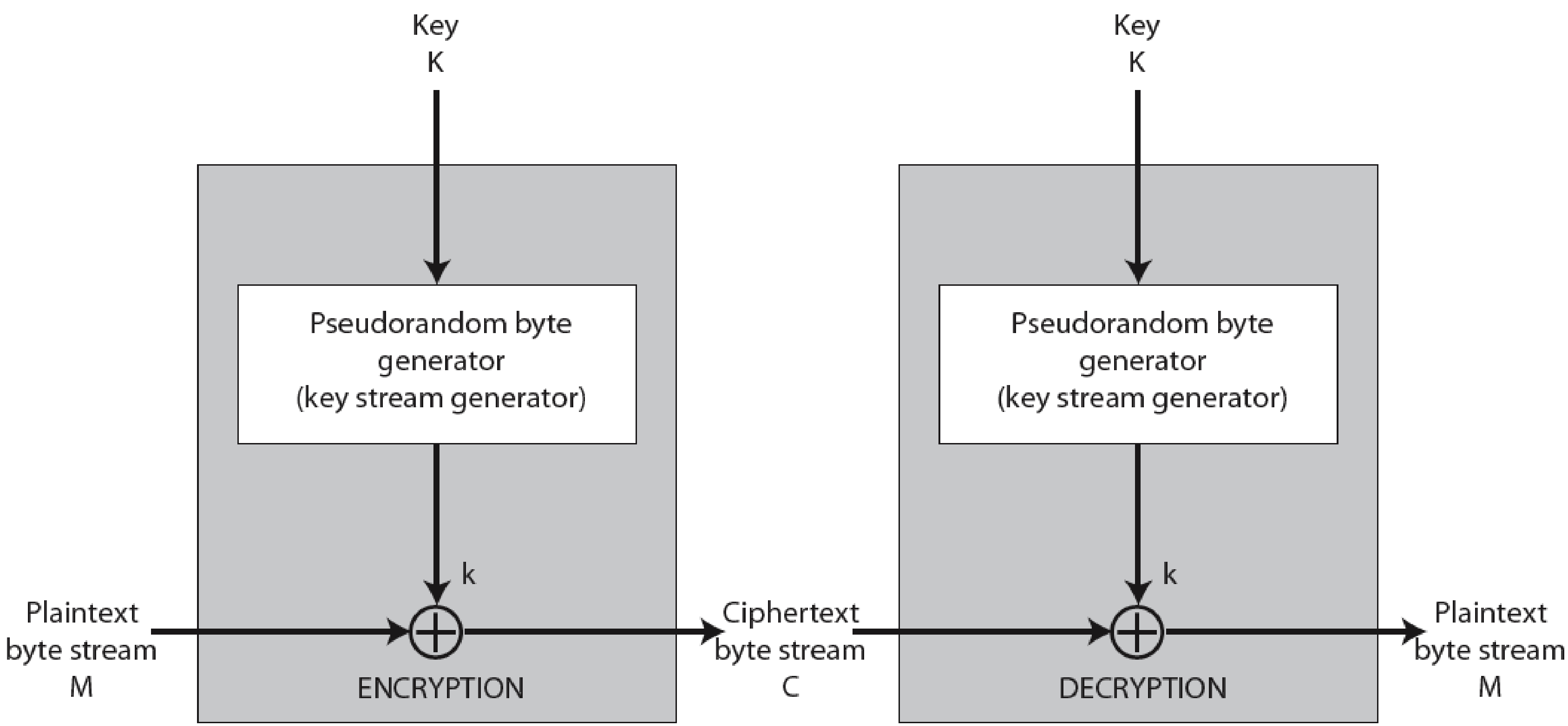


w[40, 43]
Add round key
Inverse sub bytes
Inverse shift rows
Inverse mix cols
Add round key
Round 1
Inverse mix cols
w[36, 39]
Inverse sub bytes
Inverse shift rows
Inverse mix cols
Add round key
Round 9
Inverse mix cols
w[4, 7]
Inverse sub bytes
Inverse shift rows
Add round key
Round 10
Expand key
w[0, 3]
Key
Plaintext

Stream Ciphers

- process message bit by bit (as a stream)
- have a pseudo random **keystream**
- combined (XOR) with plaintext bit by bit
- randomness of **stream key** completely destroys statistically properties in message
  - $C_i = M_i \text{ XOR } StreamKey_i$
- but must never reuse stream key
  - otherwise can recover messages

Stream Cipher Structure



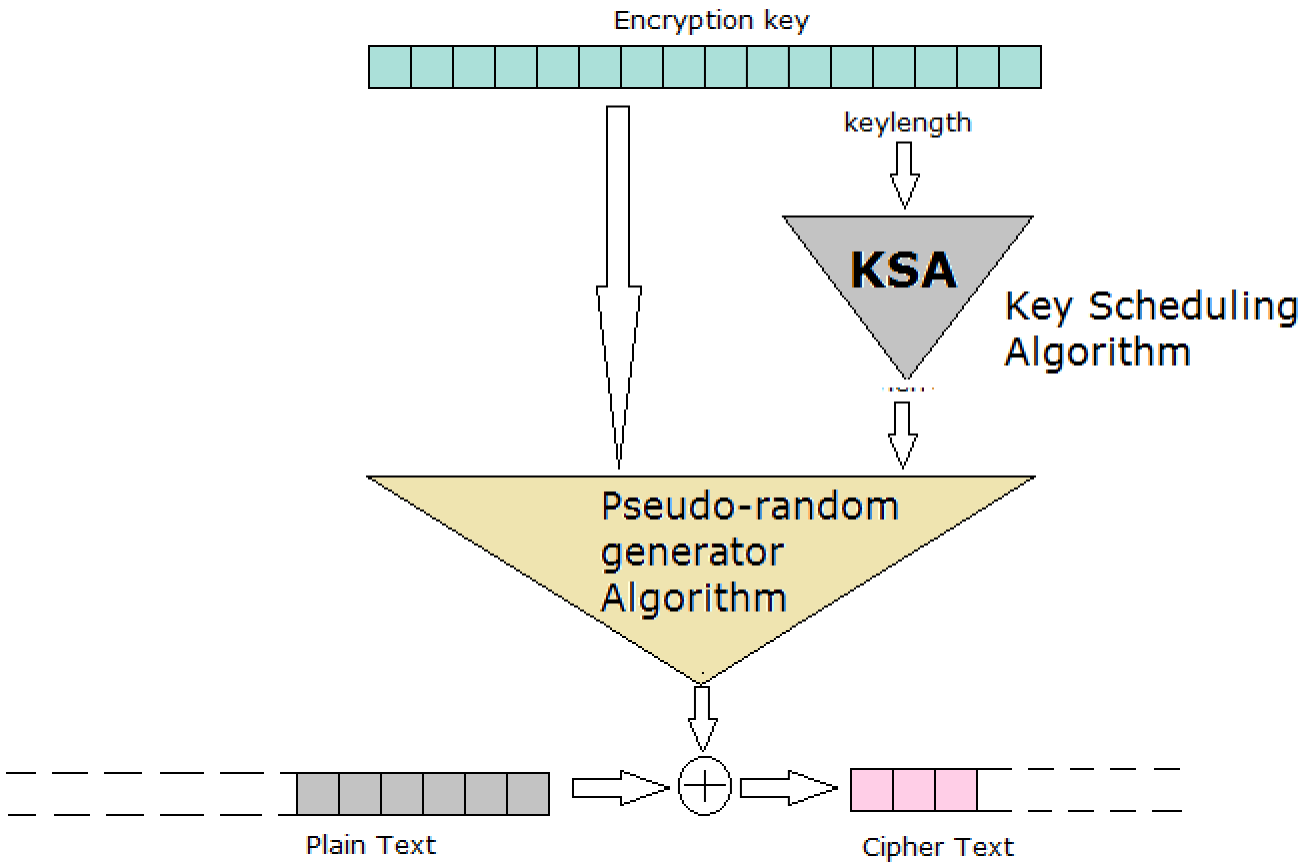
Stream Cipher Properties

- some design considerations are:
  - long period with no repetitions
  - statistically random
  - depends on large enough key
  - large linear complexity
- properly designed, can be as secure as a block cipher with same size key
- but usually simpler & faster

RC4

- Stream Cipher
- Ron Rivest design, simple but effective
- variable key size, byte-oriented stream cipher
- widely used (web SSL/TLS, wireless WEP/WPA)
- key forms random permutation of all 8-bit values
- uses that permutation to scramble input information processed a byte at a time

Schematic Representation of RC4



RC4 Key Schedule

- starts with an array S of numbers: 0..255
- A temporary vector T is also created
- If the length of key K is 256 bytes ,then K is transferred to T
- For a key of length ‘ keylen’ bytes, the first keylen elements of T are copied from K & then K is repeated as many times as necessary to fill out T.

- **Initialization**

```
for i = 0 to 255 do
   S[i] = i;
   T[i] = K[i mod keylen];
```

- **Initial permutation of S**

```
j = 0;
for i = 0 to 255 do
   j = (j + S[i] + T[i]) (mod 256)
   swap (S[i], S[j])
```

RC4 Encryption (1)

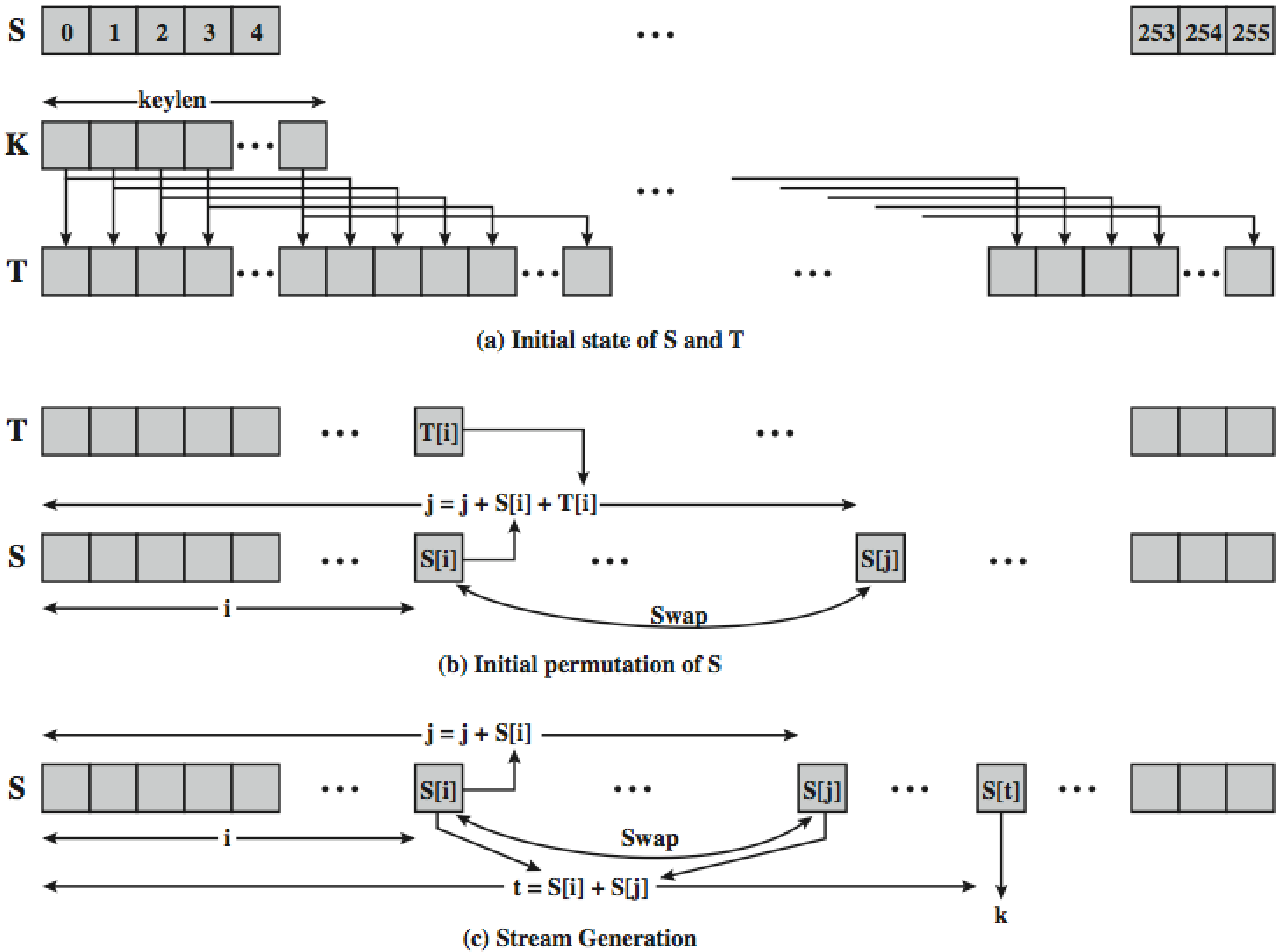
- encryption continues shuffling array values
- Stream Generation

```
i,j = 0;
While (true)
    i = (i + 1) mod 256
    j = (j + S[i]) mod 256
    swap(S[i], S[j])
    t = (S[i] + S[j]) mod 256
    K = S[t];
```

RC4 Encryption (2)

- To encrypt , XOR the value k with the next byte of plain text.
- To decrypt , XOR the value k with the next byte of cipher text

RC4 Overview



RC4 Security

- claimed secure against known attacks
  - have some analysis, none practical
- result is very non-linear
- since RC4 is a stream cipher, must **never reuse a key**

RC4

- Divided into 2 parts

  (i) Key Scheduling Algorithm (KSA)

  (ii) Pseudo Random Generation Algorithm (PRGA)
- Run PRGA on the KSA output to generate Key stream
- XOR the data with key stream