

# **SYMMETRIC CIPHERS**

## **ADVANCED ENCRYPTION STANDARD**

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# 1. AES Origins

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# AES Origins

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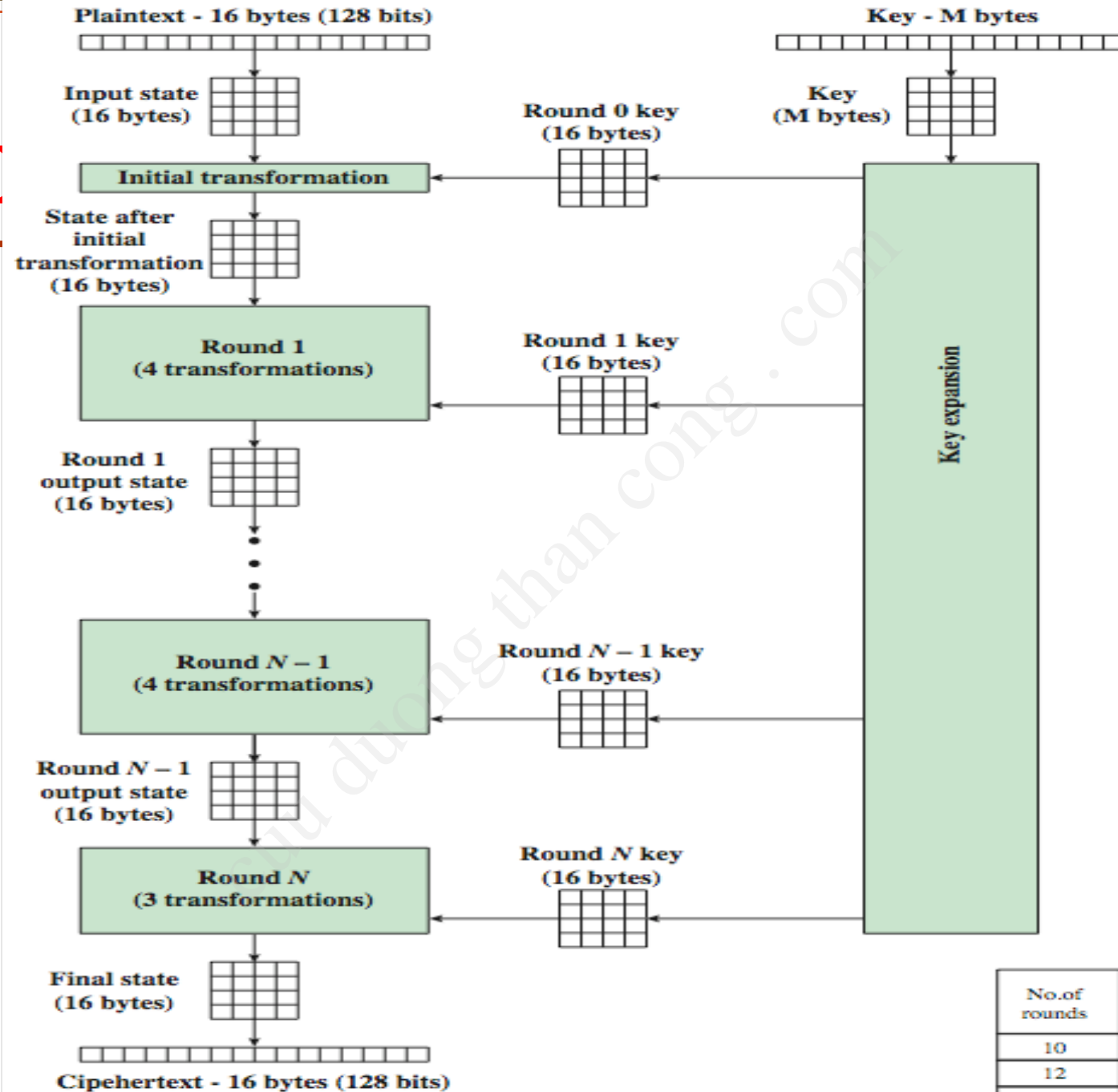
- Clear a replacement for DES was needed have theoretical attacks that can break it have demonstrated exhaustive key search attacks
- Can use Triple-DES – but slow, has small blocks

# The AES Cipher - Rijndael

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- Designed by Rijmen-Daemen in Belgium
- has 128/192/256 bit keys, 128 bit data
- Designed to have:
  - resistance against known attacks
  - speed and code compactness on many CPUs
  - design simplicity

# AES E



## 2. AES Structure

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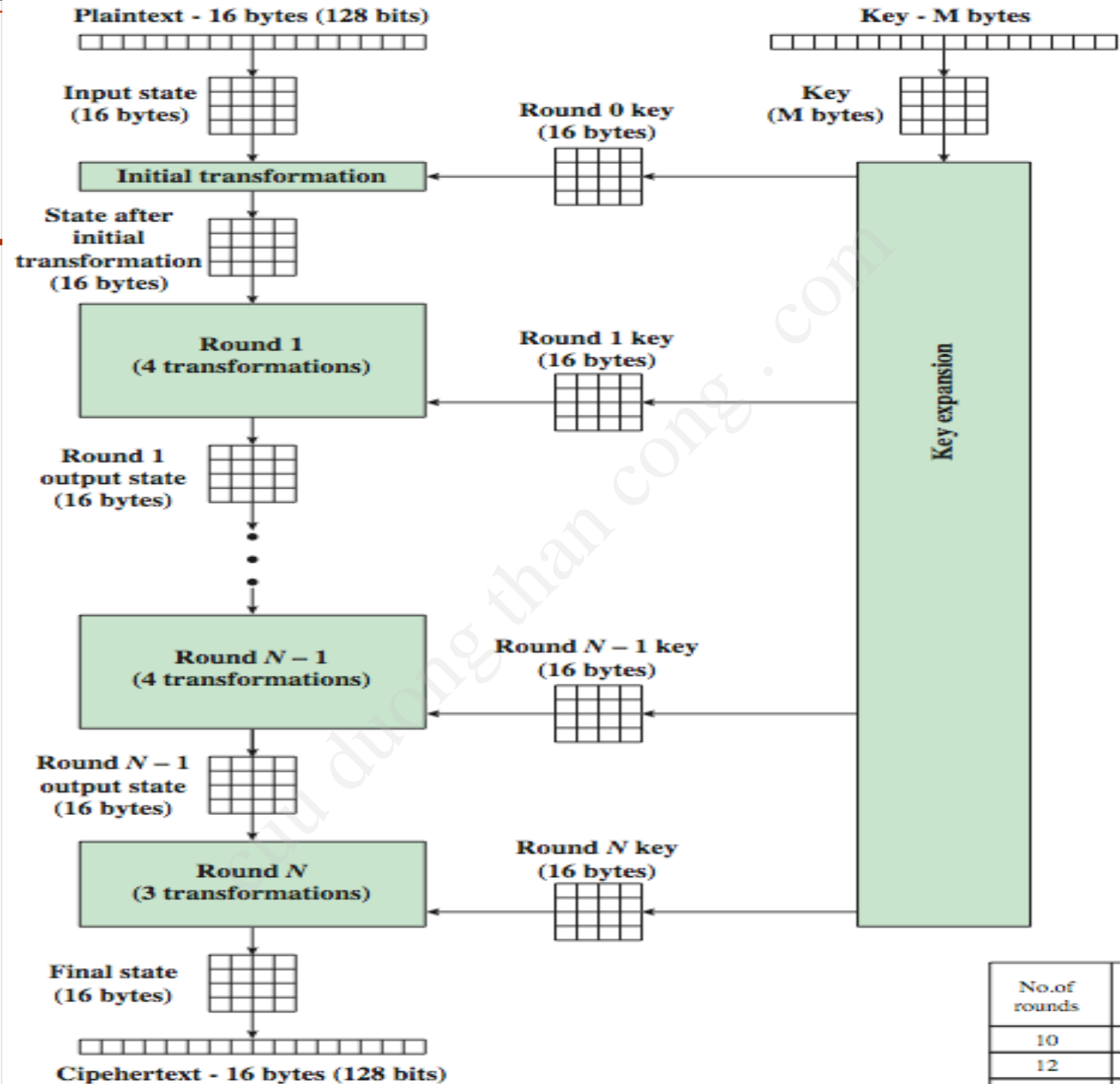
# AES Structure

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- Plaintext block size: 128 bits.
- Key length: 16, 24, or 32 bytes (128, 192, or 256 bits).
- The algorithm is referred to as AES-128, AES-192, or AES-256, depending on the key length

Chiều dài khoá (bit)	128	192	256
Kích thước khối (bit)	128	128	128
Số vòng mã (vòng)	10	12	14
Chiều dài khoá phụ (bit)	128	128	128
Chiều dài khoá mở rộng (byte)	176	208	240





# Detailed Structure

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- 128-bit block as consisting of a  $4 \times 4$  matrix of bytes, arranged as follows:

$$\begin{bmatrix} \text{byte}_0 & \text{byte}_4 & \text{byte}_8 & \text{byte}_{12} \\ \text{byte}_1 & \text{byte}_5 & \text{byte}_9 & \text{byte}_{13} \\ \text{byte}_2 & \text{byte}_6 & \text{byte}_{10} & \text{byte}_{14} \\ \text{byte}_3 & \text{byte}_7 & \text{byte}_{11} & \text{byte}_{15} \end{bmatrix}$$

- The  $4 \times 4$  matrix of bytes shown above is referred to as the **state array** in AES

# Detailed Structure



(a) Input, state array, and output

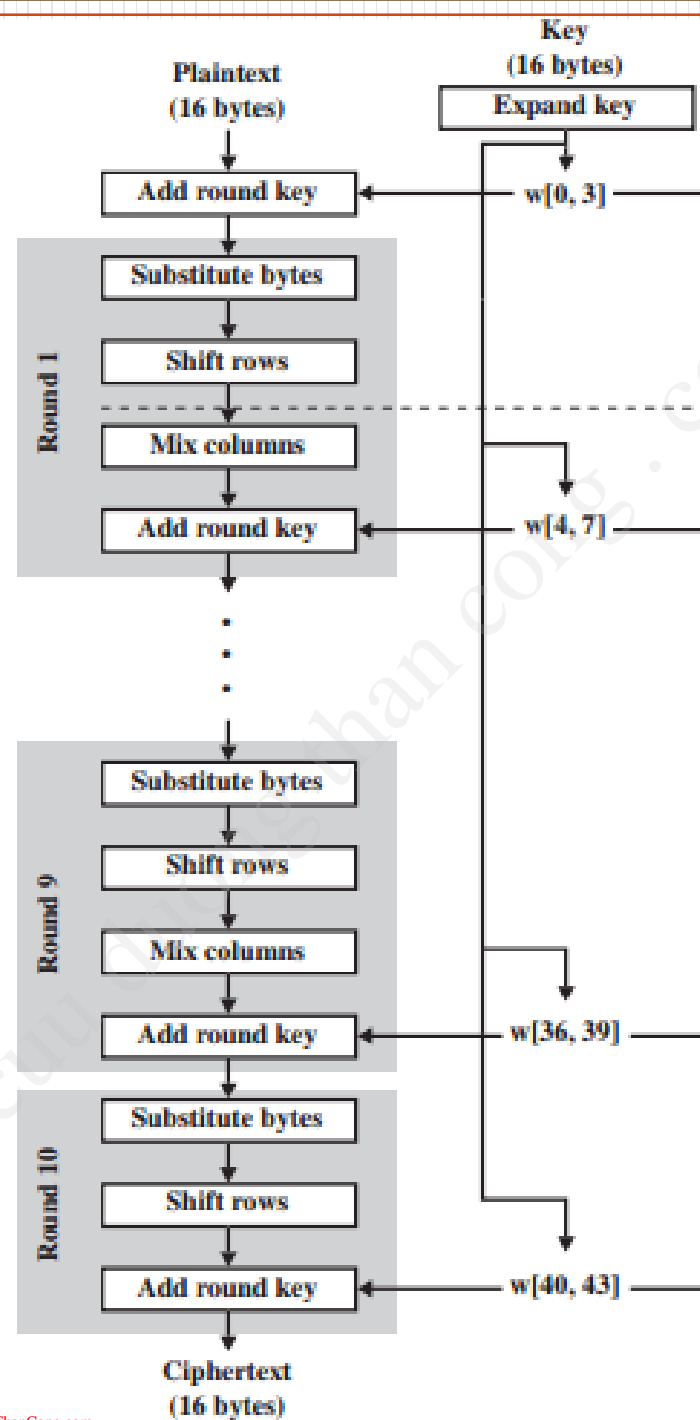
# Detailed Structure

- The key is depicted as a square matrix of bytes
- This 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



(b) Key and expanded key

# Detailed Stru



# Detailed Structure

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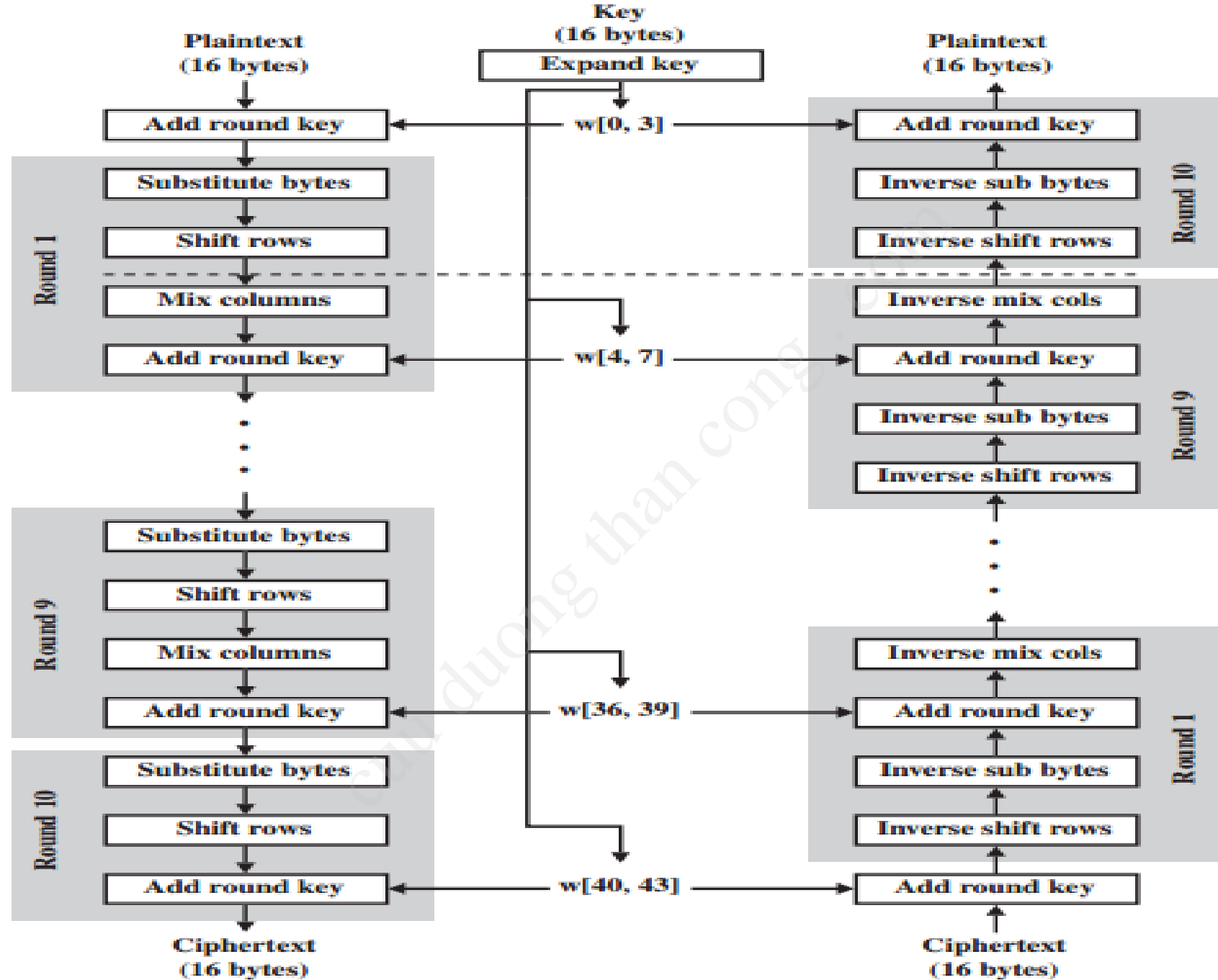
Four different stages are used, one of permutation and three of substitution:

- **Substitute bytes:** Uses an S-box to perform a byte-by-byte substitution of the block
- **Shift Rows:** A simple permutation
- **Mix Columns:** A substitution that makes use of arithmetic over
- **Add Round Key:** A simple bitwise XOR of the current block with a portion of the expanded key

# Detailed Structure

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- For both encryption and decryption, the cipher begins with an Add Round Key stage, followed by nine rounds that each includes all four stages, followed by a tenth round of three stages.
- Only the Add Round Key stage makes use of the key



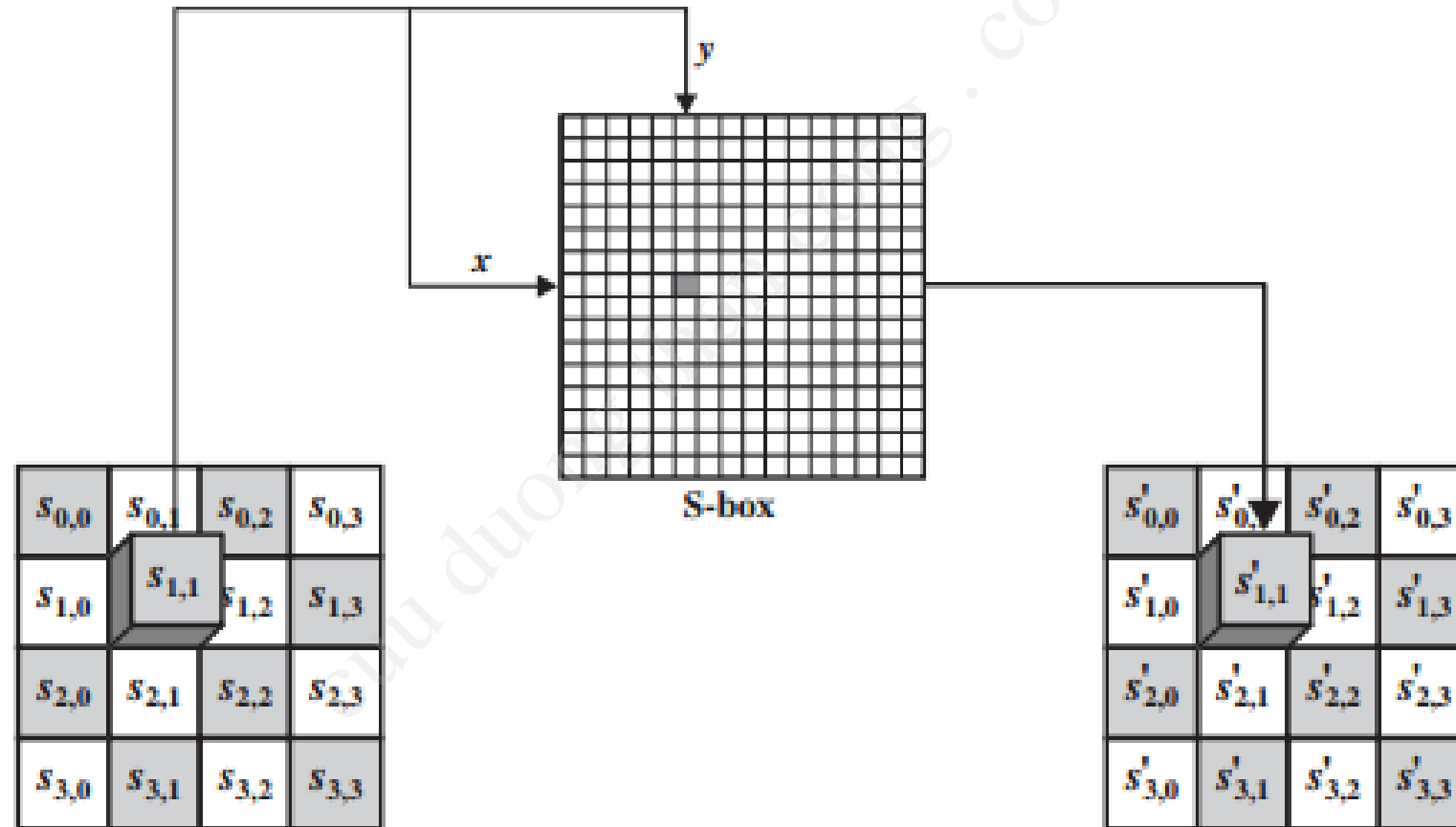


## a. Substitute Bytes Transformation

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- Each individual byte of State is mapped into a new byte in S-Box
- The leftmost 4 bits of the byte are used as a row value and the rightmost 4 bits are used as a column value.
- These row and column values serve as indexes into the S-box to select a unique 8-bit output value

# Substitute Bytes Transformation (cont.)



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

# Substitute Bytes Transformation

- For example, the hexadecimal value {95} references row 9, column 5 of the S-box, which contains the value .Accordingly, the value is mapped into the value.
- Here is an example of the SubBytes transformation:

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

→

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

## b. ShiftRows Transformation

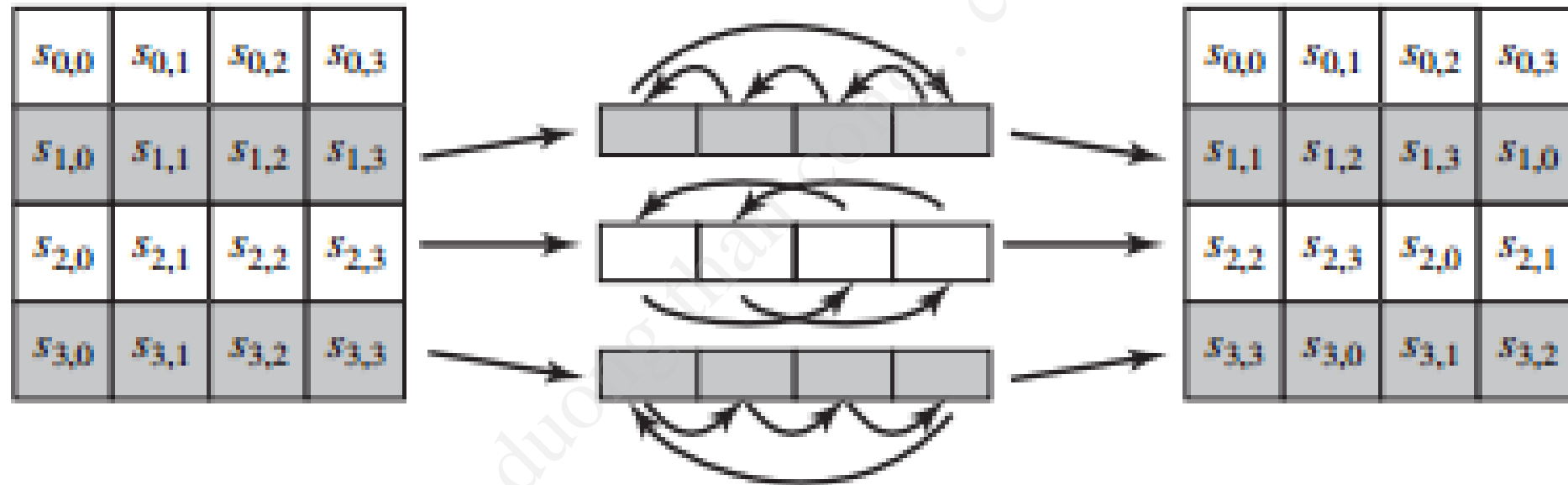
- The forward shift row transformation, called ShiftRows.
- The first row of State is not altered. For the second row, a 1-byte circular left shift is performed. For the third row, a 2-byte circular left shift is performed. For the fourth row, a 3-byte circular left shift is performed

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

# ShiftRows Transformation



(a) Shift row transformation

## c. MixColumns Transformation

- Each byte of a column is mapped into a new value that is a function of all four bytes in that column. The transformation can be defined by the following matrix multiplication on State

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

# MixColumns Transformation

- the individual additions and multiplications are performed in  $GF(2^8)$ .

$$s'_{0,j} = (2 \cdot s_{0,j}) \oplus (3 \cdot s_{1,j}) \oplus s_{2,j} \oplus s_{3,j}$$

$$s'_{1,j} = s_{0,j} \oplus (2 \cdot s_{1,j}) \oplus (3 \cdot s_{2,j}) \oplus s_{3,j}$$

$$s'_{2,j} = s_{0,j} \oplus s_{1,j} \oplus (2 \cdot s_{2,j}) \oplus (3 \cdot s_{3,j})$$

$$s'_{3,j} = (3 \cdot s_{0,j}) \oplus s_{1,j} \oplus s_{2,j} \oplus (2 \cdot s_{3,j})$$

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



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



## d. Add Round Key Transformation

- XOR state with 128-bits of the round key

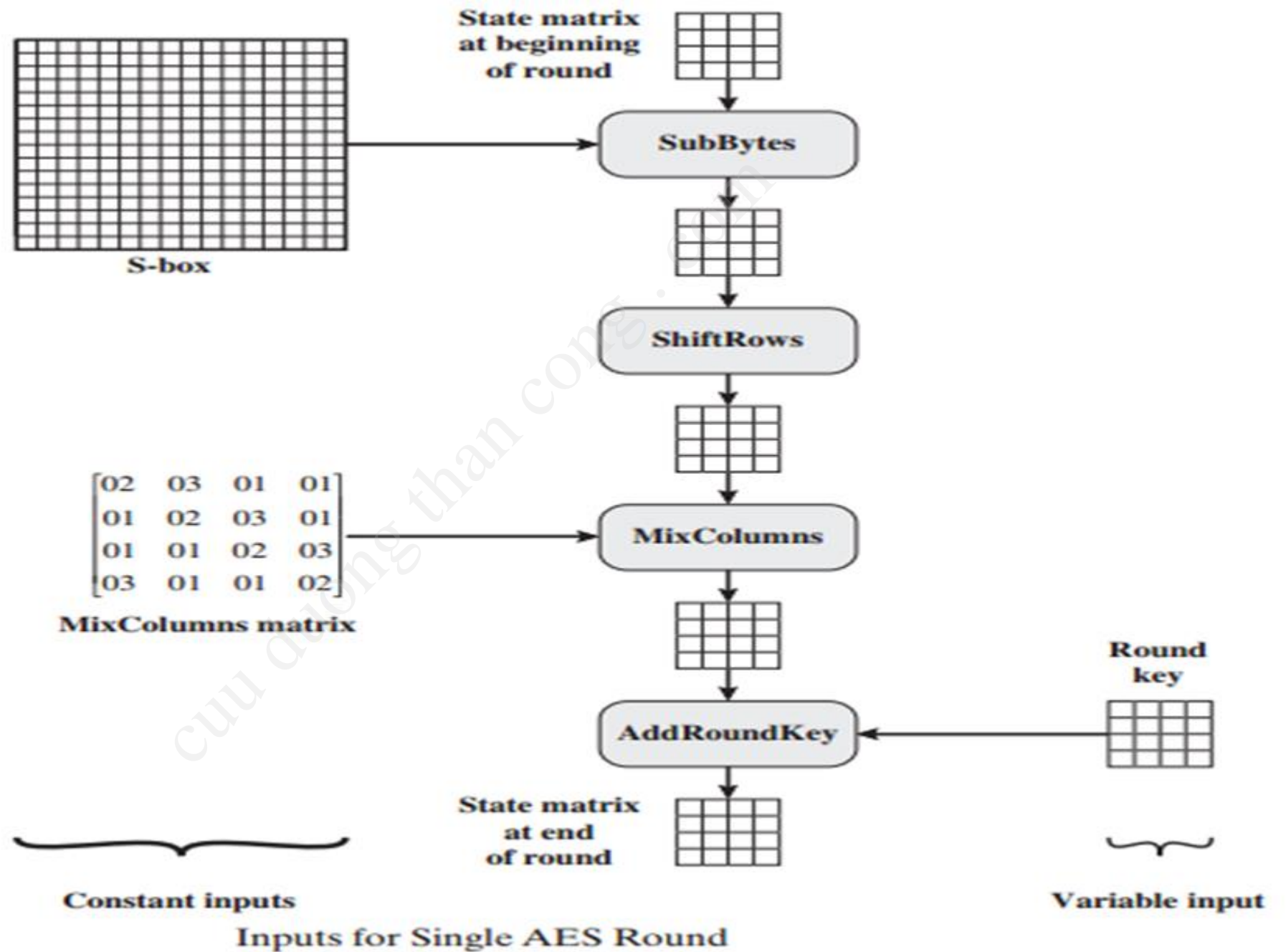
47	40	A3	4C
37	D4	70	9F
94	E4	3A	42
ED	A5	A6	BC

 $\oplus$ 

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

 $=$ 

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



# 3. Aes Key Expansion

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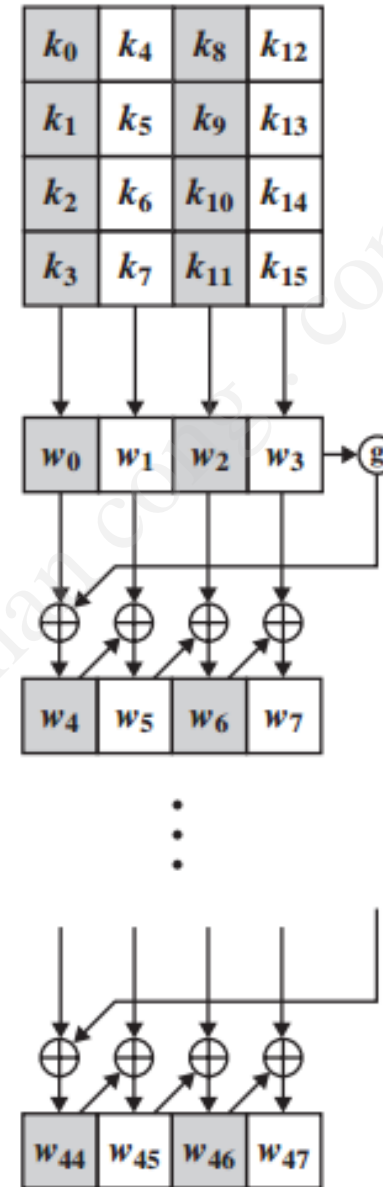
# Key Expansion Algorithm

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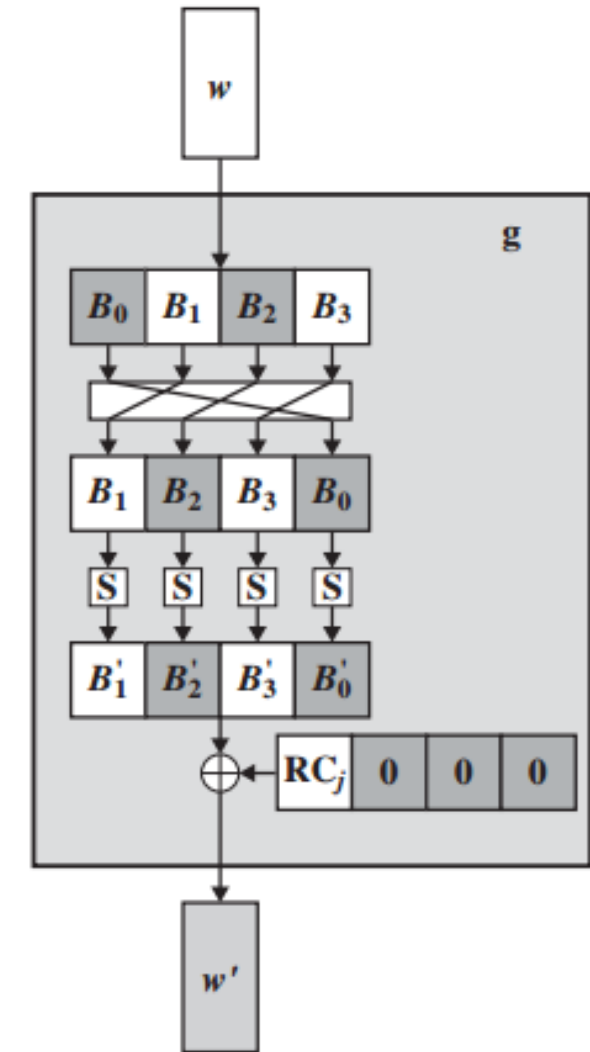
- Input a four-word (16-byte) key and produces a linear array of 44 words (176 bytes).
- This is sufficient to provide a four-word round key for the initial Add Round Key stage and each of the 10 rounds of the cipher.

# Key Expansion Algo

- $w[i] = w[i-1] \oplus w[i-4]$ .
- For a word whose position in the warray is a multiple of 4: a more complex function is used (g)



(a) Overall algorithm



(b) Function g

# Key Expansion Algorithm

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

- For example, suppose that the round key for round 8 is

EA D2 73 21 B5 8D BA D2 31 2B F5 60 7F 8D 29 2F

Then the first 4 bytes (first column) of the round key for round 9 are calculated as follows:

i (decimal)	temp	After RotWord	After SubWord	Rcon (9)	After XOR with Rcon	w[i-4]	w[i] = temp $\oplus$ w[i-4]
36	7F8D292F	8D292F7F	5DA515D2	1B000000	46A515D2	EAD27321	AC7766F3

## 4. AN AES EXAMPLE

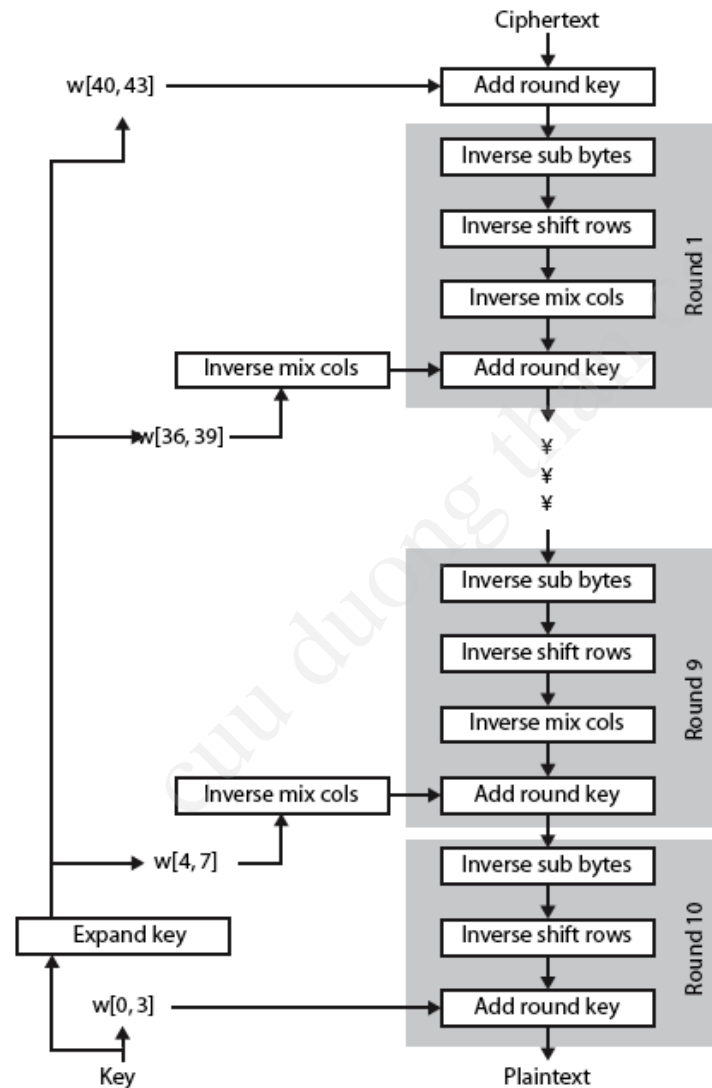
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- For this example, the plaintext is a hexadecimal palindrome. The plaintext, key, and resulting ciphertext are

Plaintext:	0123456789abcdeffedcba9876543210
Key:	0f1571c947d9e8590cb7add6af7f6798
Ciphertext:	ff0b844a0853bf7c6934ab4364148fb9



# AES Decryption



# Inverse Substitute Bytes

		y															
		0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
x	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

(b) Inverse S-box

# Inverse Shift Row Transformation

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- The inverse shift row transformation, called InvShiftRows, performs the circular shifts in the opposite direction for each of the last three rows, with a 1-byte circular right shift for the second row, and so on

# Inverse Mix Column Transformation

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

# Inverse Add Round Key Transformation

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- The inverse add round key transformation is identical to the forward add round key transformation, because the XOR operation is its own inverse

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# Thanks