Advanced Encryption Standard (AES)

History

- AES is the result of an open competition organized by NIST, US Department of Commerce.
- NIST issued call for a standard cipher in 1997
  - 15 candidates (out of 21) accepted in Jun 98
- Five candidates are sort listed.
- NIST continued to study all the available information and analyses about candidate algorithms and selected one of the algorithm, Rijndael algorithm, to propose for the AES.
- AES resists well all known cryptographic attacks and has already now achieved a high level of acceptance.

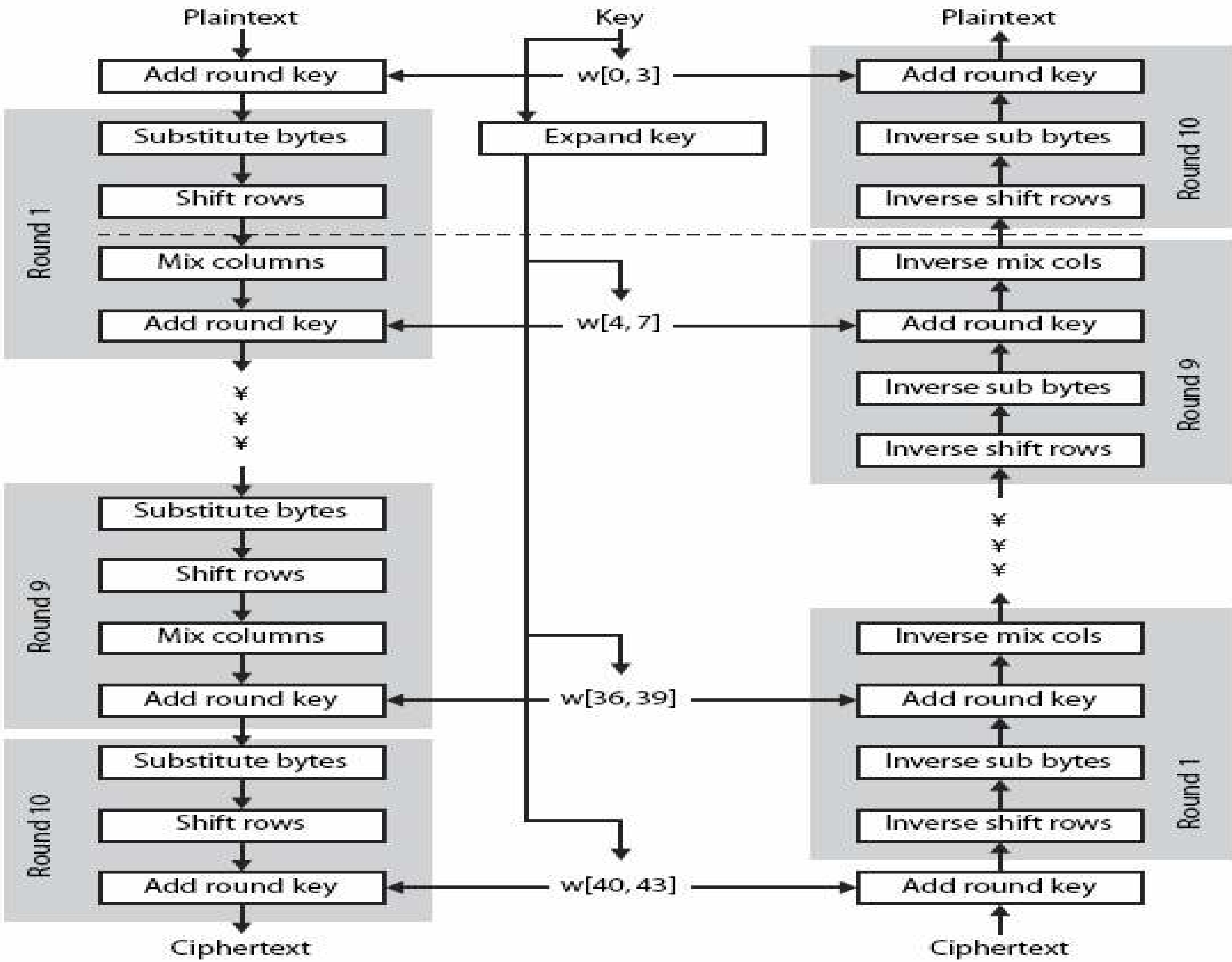
AES Overview

- AES specifies Rijndael algorithm, a symmetric block cipher that can process data blocks of 128 bits, using cipher keys with lengths of 128, 192 and 256 bits.
- It may be referred to as AES-128, AES-192 and AES-256.
- AES operates on a 4×4 array of bytes, termed the **state** (versions of Rijndael with a larger block size have additional columns in the state).
- For Encryption, each round except last round of AES consists of four stages.
  - SubBytes
  - ShiftRows
  - MixColumns
  - AddRoundKey
- The final round omits the MixColumns stage.

AES Overview (contd)

- A number of AES parameters depend on the key length.

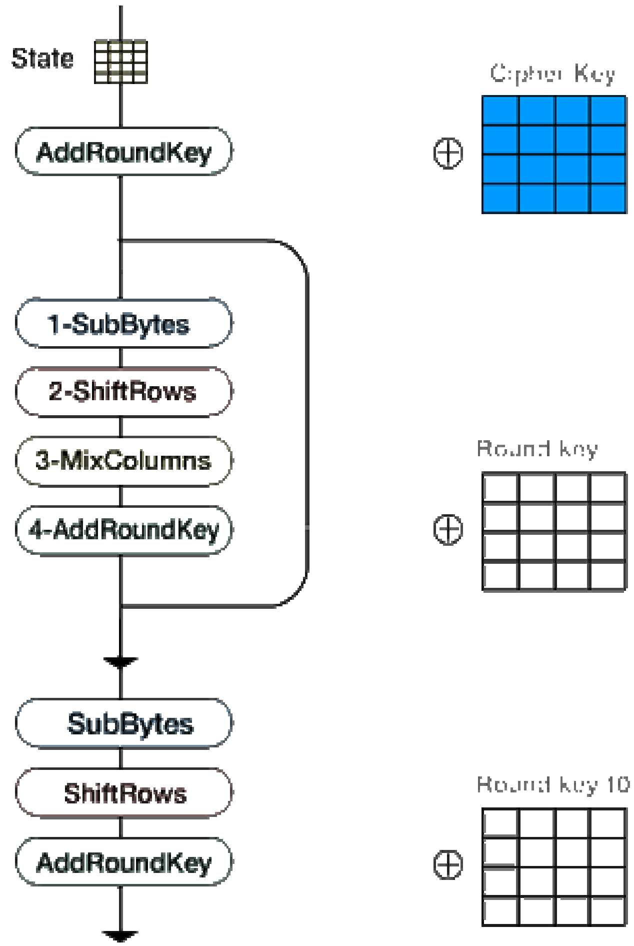
Key size (words/bytes/bits)	4/16/128	6/24/192	8/32/256
Plaintext block size (words/bytes/blts)	4/16/128	4/16/128	4/16/128
Number of rounds	10	12	14
Round key size (words/bytes/bits)	4/16/128	4/16/128	4/16/128
Expanded key size (words/bytes)	44/176	52/208	60/240



(a) Encryption

(b) Decryption

AES Structure



Algorithm Parameters, Symbols and Functions used in Description of AES

- AddRoundKey( )
  - Transformation in the cipher and Inverse cipher in which a Round Key is added to the state using an XOR operation.
  - The length of a Round key equals the size of the State. (i.e. for N_b=4, Round key length equals 128bits/16 bytes)
- InvMixColumns( )
  - Transformation in the Inverse Cipher that is the inverse of MixColumns()
- InvShiftRows( )
  - Transformation in the Inverse Cipher that is the inverse of ShiftRows( )
- InvSubBytes( )
  - Transformation in the Inverse Cipher that is the inverse of SubBytes( )
- K is Cipher Key
- MixColumns( )
  - Transformation in the Cipher that takes all of the columns of the state and mixes their data (independently of one another) to produce new columns
- N_b Number of columns (32-bit words) comprising the state.
  - For AES $N_b = 4$

Algorithm Parameters, Symbols and Functions used in Description of AES

- N_k Number of 32-bit words comprising the Cipher key.
  - For AES, $N_k = 4, 6$ or 8 (i.e. key length 128, 192 or 256 bits)
- N_r Number of rounds, which is a function of N_k and N_b.
  - For AES $N_r = 10, 12$ or 14.
- Rcon [ ] The round constant word array.
- RotWord( )
  - Function used in the Key Expansion routine that takes a four- byte word and perform a cyclic permutation.
- ShiftRows( )
  - Transformation in the Cipher that processes the State by cyclically shifting the last three rows of the State by different offsets.
- SubBytes( )
  - Transformation in the Cipher that processes the State using a nonlinear byte substitution table (S–box) that operates on each of the State bytes independently.
- • Finite field multiplication.

State

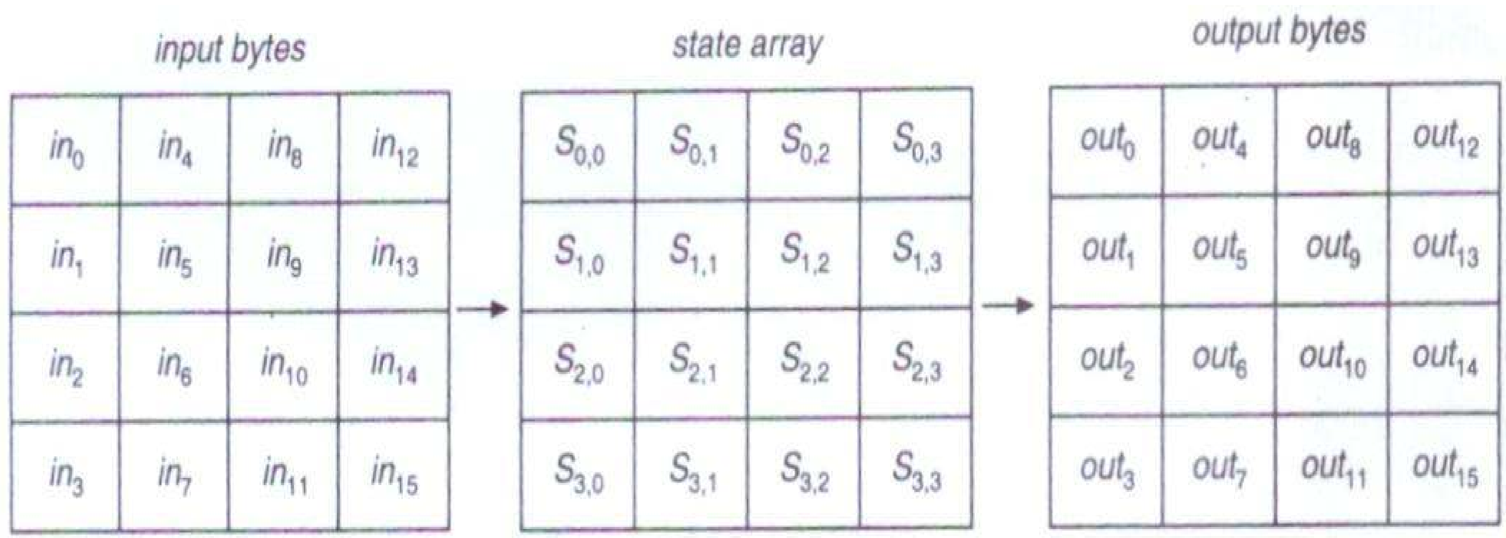
- Definition:
  - AES algorithm's operations are performed on a two-dimensional array of bytes called the ***State***.

- The State consists of four rows of bytes, each containing N_b bytes, where N_b is the block length divided by 32.

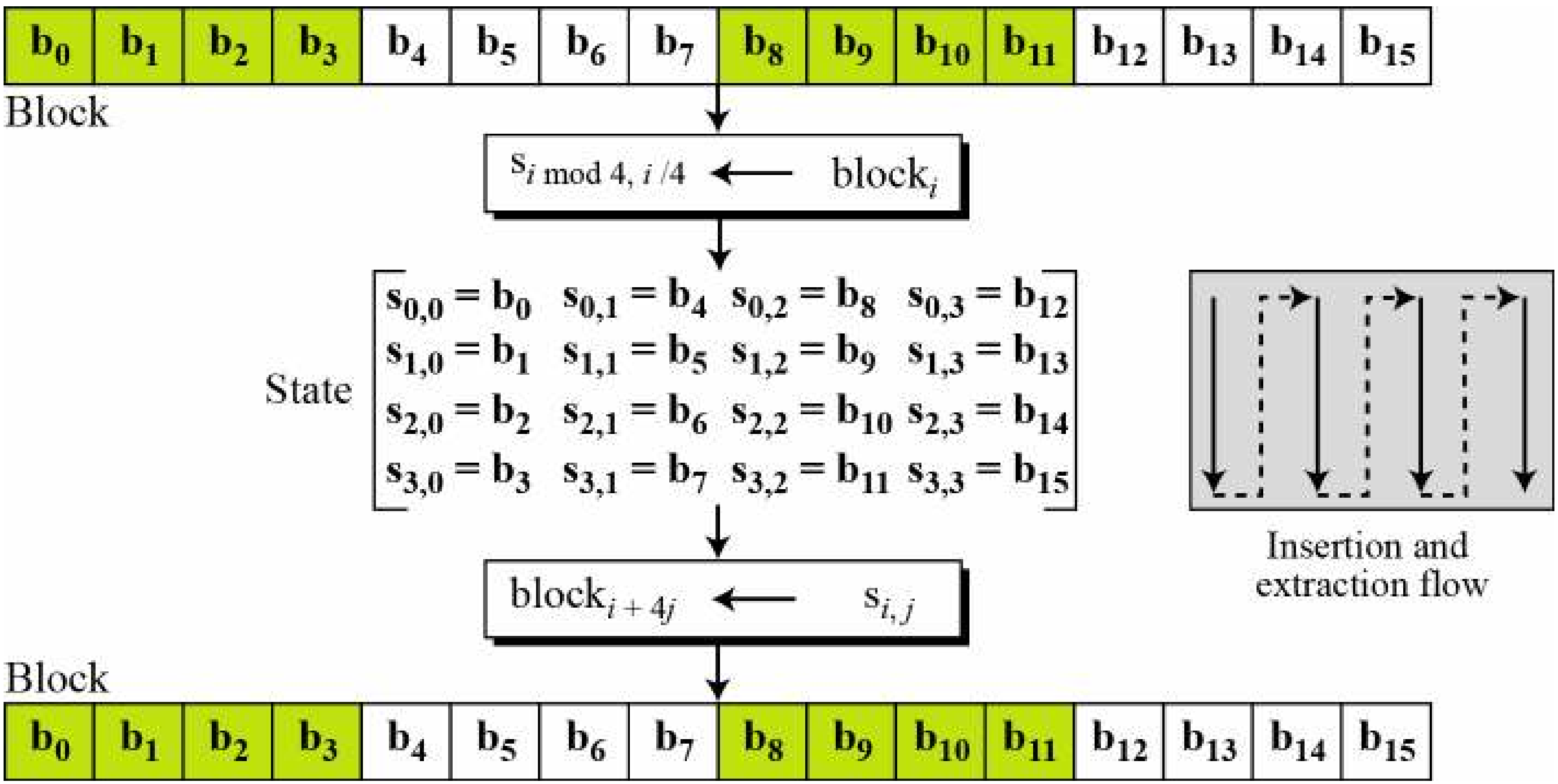
- State array denoted by symbol S.
  - Each individual byte has two indices.
    - Row number r, $0 \le r < 4$
    - Column number c, $0 \le c < N_b$

State (contd)

- The input, array of bytes in_0, in_1, … in_{15}, is copied into the State array as shown in figure.



- The cipher operations are then conducted on this State array, after which its final value is copied to the output – the array of bytes out_0,out_1,…,out_{15}.



b_0 b_1 b_2 b_3 b_4 b_5 b_6 b_7 b_8 b_9 b_{10} b_{11} b_{12} b_{13} b_{14} b_{15}
Block
$s_{i \bmod 4,\, i/4} \leftarrow \text{block}_i$
State
$s_{0,0} = b_0$ $s_{0,1} = b_4$ $s_{0,2} = b_8$ $s_{0,3} = b_{12}$
$s_{1,0} = b_1$ $s_{1,1} = b_5$ $s_{1,2} = b_9$ $s_{1,3} = b_{13}$
$s_{2,0} = b_2$ $s_{2,1} = b_6$ $s_{2,2} = b_{10}$ $s_{2,3} = b_{14}$
$s_{3,0} = b_3$ $s_{3,1} = b_7$ $s_{3,2} = b_{11}$ $s_{3,3} = b_{15}$
$\text{block}_{i+4j} \leftarrow s_{i,j}$
Block
b_0 b_1 b_2 b_3 b_4 b_5 b_6 b_7 b_8 b_9 b_{10} b_{11} b_{12} b_{13} b_{14} b_{15}
Insertion and extraction flow

GF(2^8)

- Byte $b_7b_6b_5b_4b_3b_2b_1b_0$ will have the representation as
  $b(x) = b_7x^7 + b_6x^6 + b_5x^5 + b_4x^4 + b_3x^3 + b_2x^2 + b_1x + b_0$
- Therefore, 01010111 would have the representation as 01010111
  $x^6 + x^4 + x^2 + x + 1$

Addition in Finite field

- Addition in a finite field achieved by adding the coefficients for the corresponding powers in the polynomials for the two elements
- Addition performed by EX-OR operation
  - denoted as <F, $\oplus$ > modulo 2
- Alternatively, addition of finite field elements done by modulo 2 addition of the corresponding bits in the byte.

Example:

- $(x^6 + x^4 + x^2 + x + 1) \oplus (x^7 + x + 1) = x^7 + x^6 + x^4 + x^2$ (polynomial notation)
- {01010111} $\oplus$ {10000011} = {11010100} (binary notation)
- {57} $\oplus$ {83} = {d4} (hexadecimal notation)

Multiplication

- denoted by <F{0}, • > or < F{0},
- multiplication in $GF(2^8)$ corresponds to
  - multiplication of polynomials modulo an irreducible polynomial of degree 8
  - irreducible polynomial is the one whose divisors are one and itself only
  - for AES, the irreducible polynomial is $m(x) = x^8 + x^4 + x^3 + x + 1$ (i.e. {01}{1B})

Example:

{57} • {83} = {c1}.

$$(x^6 + x^4 + x^2 + x + 1) (x^7 + x + 1)$$

$$= x^{13} + x^{11} + x^9 + x^8 + x^7 + x^7 + x^5 + x^3 + x^2 + x + x^6 + x^4 + x^2 + x + 1$$

$$= x^{13} + x^{11} + x^9 + x^8 + x^6 + x^5 + x^4 + x^3 + 1 \qquad \text{------(1)}$$

Multiplication (contd)

$(x^{13} + x^{11} + x^9 + x^8 + x^6 + x^5 + x^4 + x^3 + 1)$ modulo $(x^8 + x^4 + x^3 + x + 1)$
 = x7 + x6 + 1 = {c1}

Sol^n : $x^8 + x^4 + x^3 + x + 1$ is a m(x) means irreducible polynomial.

Multiply this m(x) with x^5 (because highest power in eq. (1) is 13.)

$(x^8 + x^4 + x^3 + x + 1)(x^5) = x^{13} + x^9 + x^8 + x^6 + x^5$ ----(2)

- Now addition of eq. (1) and (2),

  $(x^{13} + x^{11} + x^9 + x^8 + x^6 + x^5 + x^4 + x^3 + 1) \oplus (x^{13} + x^9 + x^8 + x^6 + x^5)$

  $= x^{11} + x^4 + x^3 + 1$ ----- (3)
- Multiply m(x) with x^3 ((because highest power in eq. (3) is 11.)

  $(x^8 + x^4 + x^3 + x + 1)(x^3) = x^{11} + x^7 + x^6 + x^4 + x^3$ ----(4)
- Now addition of eq. (3) and (4),

  $(x^{11} + x^7 + x^6 + x^4 + x^3) \oplus (x^{11} + x^4 + x^3 + 1) = x^7 + x^6 + 1$ = {11000001}

  = {c1}

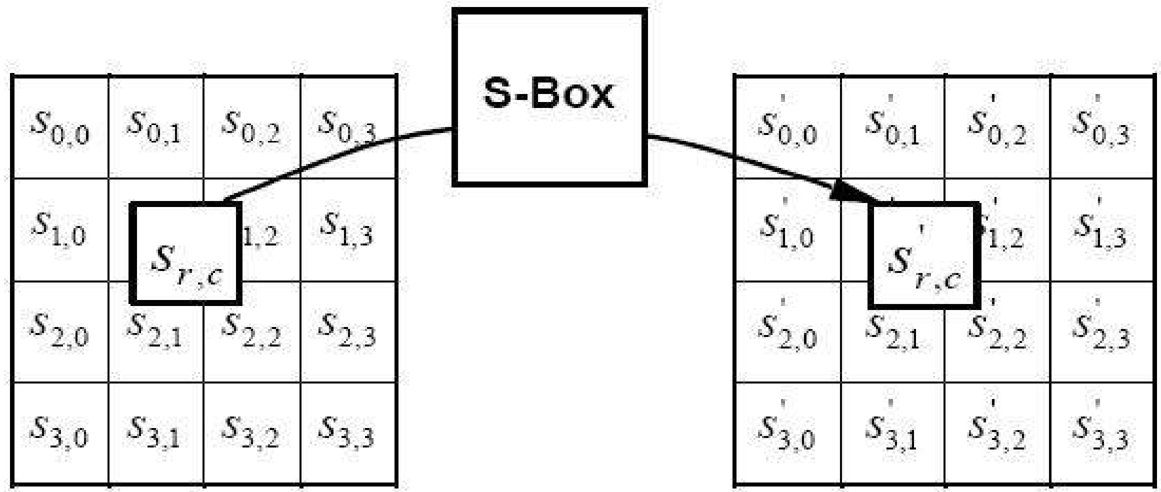
Pseudo code for AES

- N_b = 4 for block size 128 bits

```
Cipher(byte in[4*Nb],byte out[4*Nb],word w[Nb*(Nr+1)])
begin
     byte state[4,Nb]
     state = in
     AddRoundKey(state, w[0, Nb-1])
     for round = 1 step 1 to Nr-1
          SubBytes(state)
          ShiftRows(state)
          MixColumns(state)
          AddRoundKey(state,w[round*Nb,(round+1)*Nb-1])
     end for
     SubBytes(state)
     ShiftRows(state)
     AddRoundKey(state, w[Nr*Nb, (Nr+1)*Nb-1])
     out = state
end
```

SubBytes( ) Transformation

- It is a non-linear byte substitution that operates independently on each byte of the State using a substitution table (S- box).
- 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}



SubBytes( ) Transformation (contd)

- AES S-box

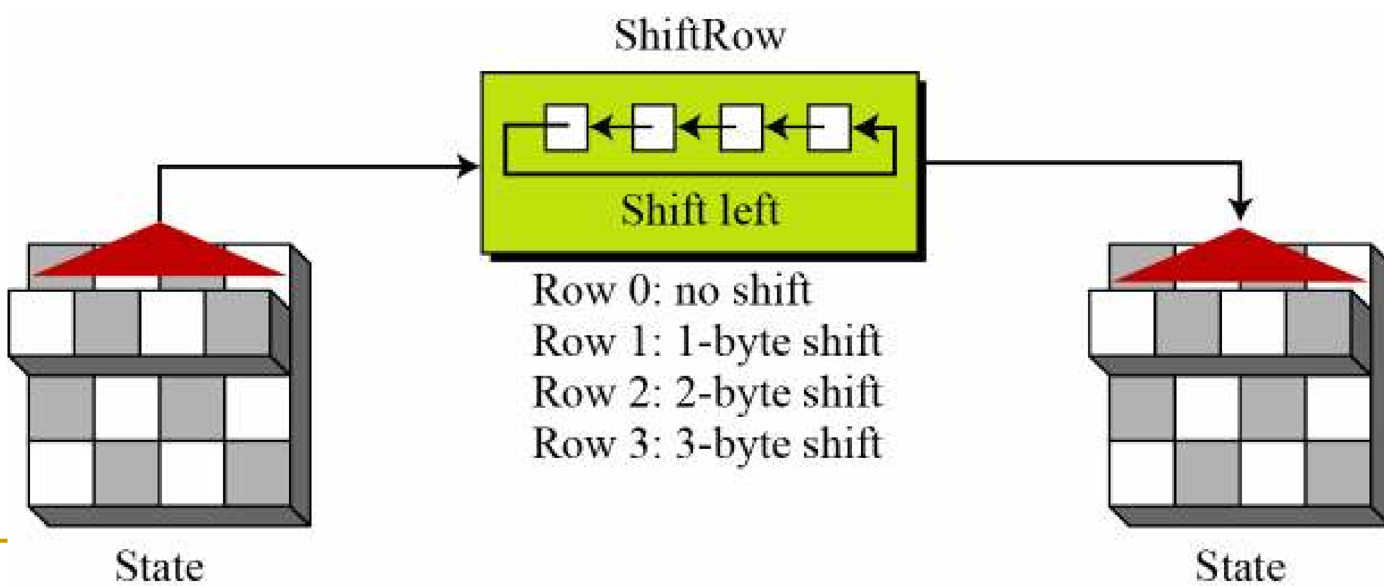
		y															
		0	1	2	3	4	5	6	7	8	9	a	b	c	d	e	f
x	0	63	7c	77	7b	f2	6b	6f	c5	30	01	67	2b	fe	d7	ab	76
	1	ca	82	c9	7d	fa	59	47	f0	ad	d4	a2	af	9c	a4	72	c0
	2	b7	fd	93	26	36	3f	f7	cc	34	a5	e5	f1	71	d8	31	15
	3	04	c7	23	c3	18	96	05	9a	07	12	80	e2	eb	27	b2	75
	4	09	83	2c	1a	1b	6e	5a	a0	52	3b	d6	b3	29	e3	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

- Inverse S-box used in the **InvSubBytes()** transformation

		y															
		0	1	2	3	4	5	6	7	8	9	a	b	c	d	e	f
	0	52	09	6a	d5	30	36	a5	38	bf	40	a3	9e	81	f3	d7	fb
	1	7c	e3	39	82	9b	2f	ff	87	34	8e	43	44	c4	de	e9	cb
	2	54	7b	94	32	a6	c2	23	3d	ee	4c	95	0b	42	fa	c3	4e
	3	08	2e	a1	66	28	d9	24	b2	76	5b	a2	49	6d	8b	d1	25
	4	72	f8	f6	64	86	68	98	16	d4	a4	5c	cc	5d	65	b6	92
	5	6c	70	48	50	fd	ed	b9	da	5e	15	46	57	a7	8d	9d	84
	6	90	d8	ab	00	8c	bc	d3	0a	f7	e4	58	05	b8	b3	45	06
	7	d0	2c	1e	8f	ca	3f	0f	02	c1	af	bd	03	01	13	8a	6b
x	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

ShiftRows( ) Transformation

- The bytes in the last three rows of the State are cyclically shifted over different numbers of bytes.
  - 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

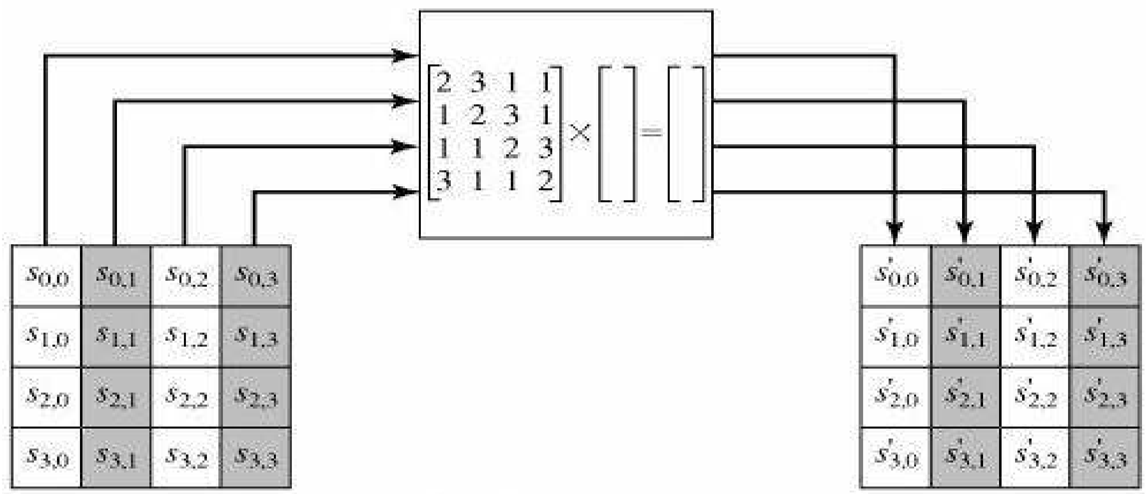


MixColumns( ) Transformation

- The transformation operates on the State column-by-column, treating each column as a four-term polynomial.
- The MixColumns stage is a substitution that makes use of arithmetic over GF(2^8).
- Constant matrices used by MixColumns and InvMixColumns

$$\underset{C}{\begin{bmatrix} 02 & 03 & 01 & 01 \\ 01 & 02 & 03 & 01 \\ 01 & 01 & 02 & 03 \\ 03 & 01 & 01 & 02 \end{bmatrix}} \xleftrightarrow{\text{Inverse}} \underset{C^{-1}}{\begin{bmatrix} 0E & 0B & 0D & 09 \\ 09 & 0E & 0B & 0D \\ 0D & 09 & 0E & 0B \\ 0B & 0D & 09 & 0E \end{bmatrix}}$$

MixColumns( ) Transformation (contd)



MixColumns( ) Transformation (contd)

$$\begin{bmatrix} s'_{0,c} \\ s'_{1,c} \\ s'_{2,c} \\ s'_{3,c} \end{bmatrix} = \begin{bmatrix} 02 & 03 & 01 & 01 \\ 01 & 02 & 03 & 01 \\ 01 & 01 & 02 & 03 \\ 03 & 01 & 01 & 02 \end{bmatrix} \begin{bmatrix} s_{0,c} \\ s_{1,c} \\ s_{2,c} \\ s_{3,c} \end{bmatrix} \quad \text{for } 0 \le c < \boldsymbol{Nb}.$$

As a result of this multiplication, the four bytes in a column are replaced by the following:

$$s'_{0,c} = (\{02\} \bullet s_{0,c}) \oplus (\{03\} \bullet s_{1,c}) \oplus s_{2,c} \oplus s_{3,c}$$

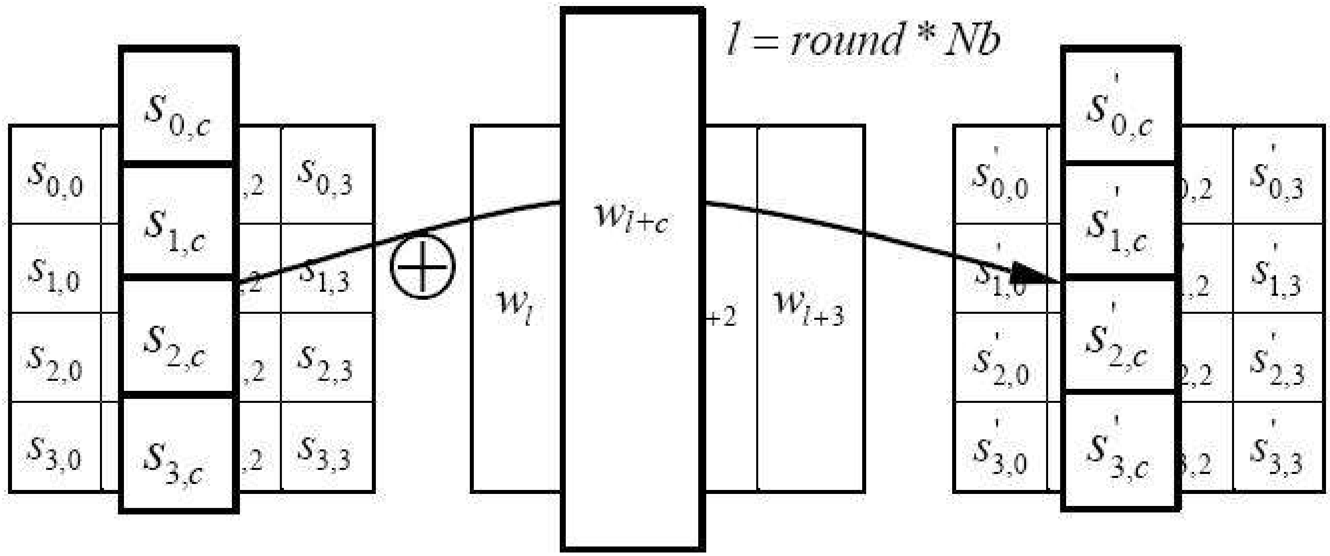
$$s'_{1,c} = s_{0,c} \oplus (\{02\} \bullet s_{1,c}) \oplus (\{03\} \bullet s_{2,c}) \oplus s_{3,c}$$

$$s'_{2,c} = s_{0,c} \oplus s_{1,c} \oplus (\{02\} \bullet s_{2,c}) \oplus (\{03\} \bullet s_{3,c})$$

$$s'_{3,c} = (\{03\} \bullet s_{0,c}) \oplus s_{1,c} \oplus s_{2,c} \oplus (\{02\} \bullet s_{3,c}).$$

AddRoundKey( ) Transformation

- A Round key is added to the State by a simple bitwise XOR operation.
- Each Round Key consists of N_b words from the key schedule.
- Inverse for decryption is identical.
  - Since XOR own inverse, with reversed keys



AES Key Expansion

- Algorithm takes the Cipher Key K and performs a Key Expansion routine to generate a key schedule.
- The Key Expansion generates a total of N_b (N_r +1) words
  - Algorithm requires an initial set of N_b words
  - Each of the N_r rounds requires N_b words of key data.
- proceeds as per
  - subword()
    - input – 4-byte word and S-box
    - output – 4 byte word after substitution
  - RotWord()
    - input – 4-byte word [a0a1a2a3]
    - output - 4-byte rotated word [a1a2a3a0]

Pseudo code for Key Expansion

```
KeyExpansion(byte key[4 * Nk], word w[Nb * (Nr + 1)], Nk)
begin
    i=0
    while (i < Nk)
        w[i] = word[key[4*i],key[4*i+1],key[4*i+2],key[4*i+3]]
        i = i + 1
    end while

    i = Nk
    while (i < Nb * (Nr + 1))
        word temp = w[i - 1]
        if (i mod Nk = 0)
            temp = SubWord(RotWord(temp)) xor Rcon[i / Nk]
        else if (Nk = 8 and i mod Nk = 4)
            temp = SubWord(temp)
        end if
    w[i] = w[i - Nk] xor temp
    i = i + 1
    end while
end
```

AES Cipher Example

- Input = 32 43 f6 a8 88 5a 30 8d 31 31 98 a2 e0 37 07 34
- Cipher Key = 2b 7e 15 16 28 ae d2 a6 ab f7 15 88 09 cf 4f 3c

AES Key Expansion Example

2b	28	ab	09
7e	ae	f7	cf
15	d2	15	4f
16	a6	88	3c

. . .

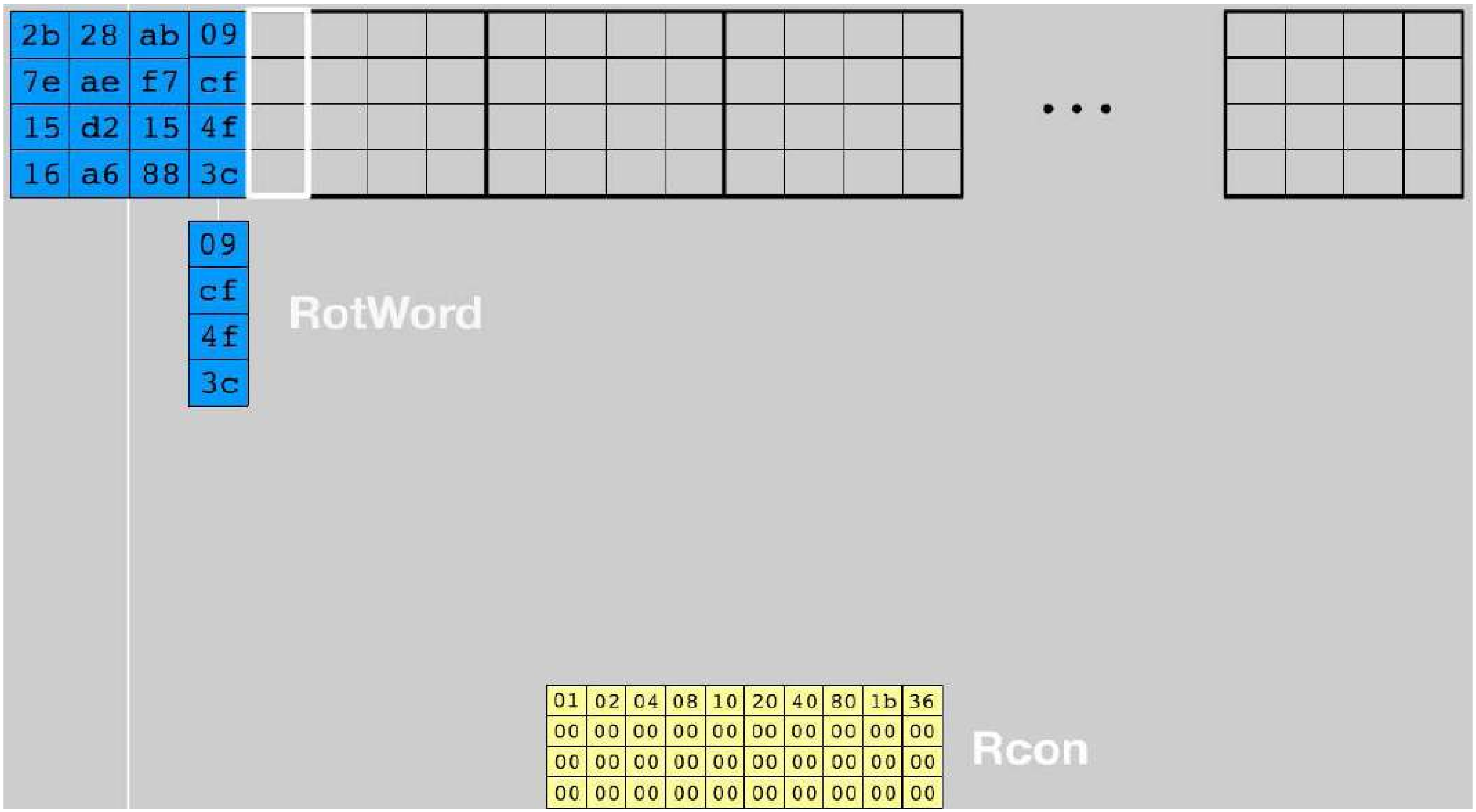
How to calculate Rcon?

Rcon table

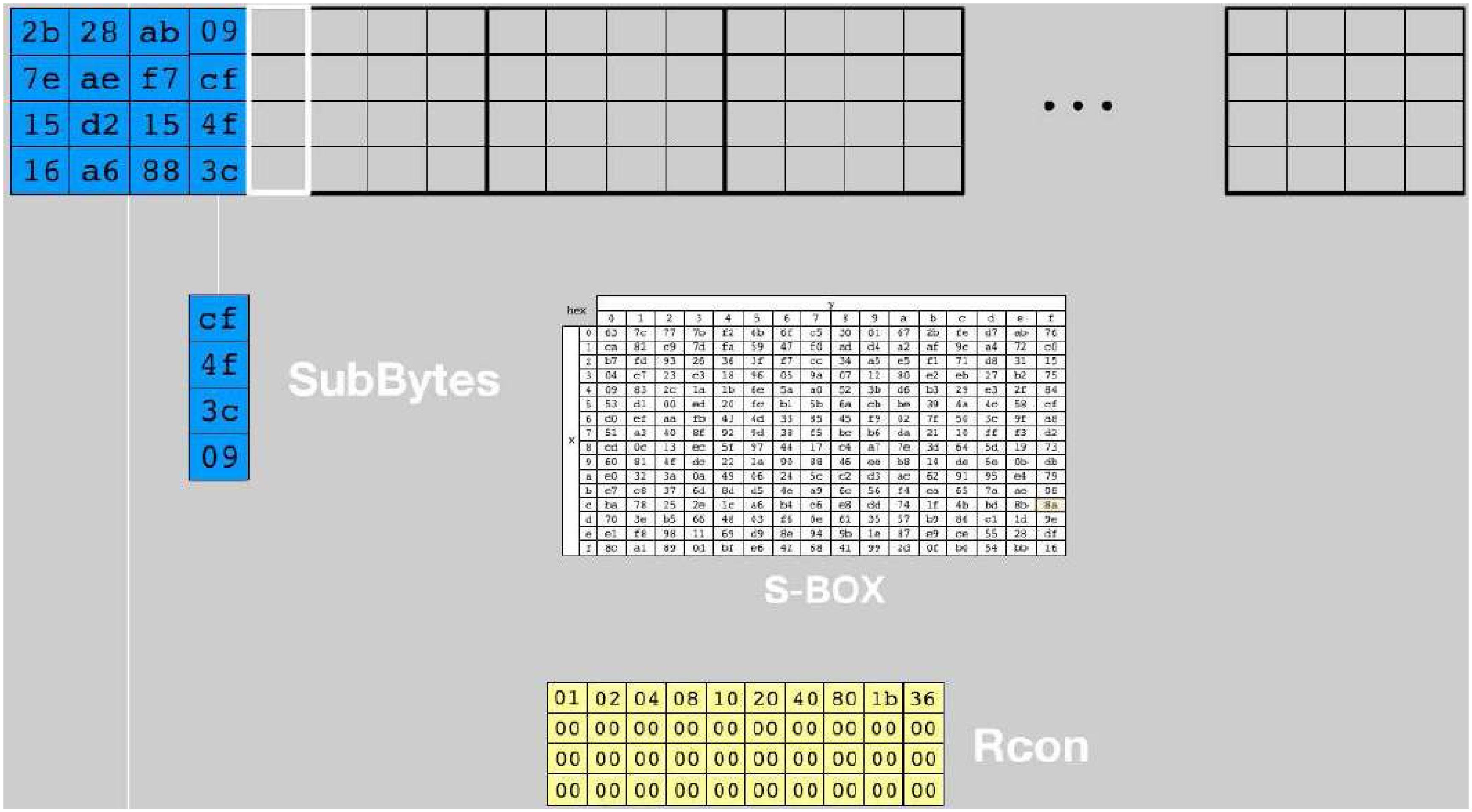
01	02	04	08	10	20	40	80	1b	36
00	00	00	00	00	00	00	00	00	00
00	00	00	00	00	00	00	00	00	00
00	00	00	00	00	00	00	00	00	00

Rcon

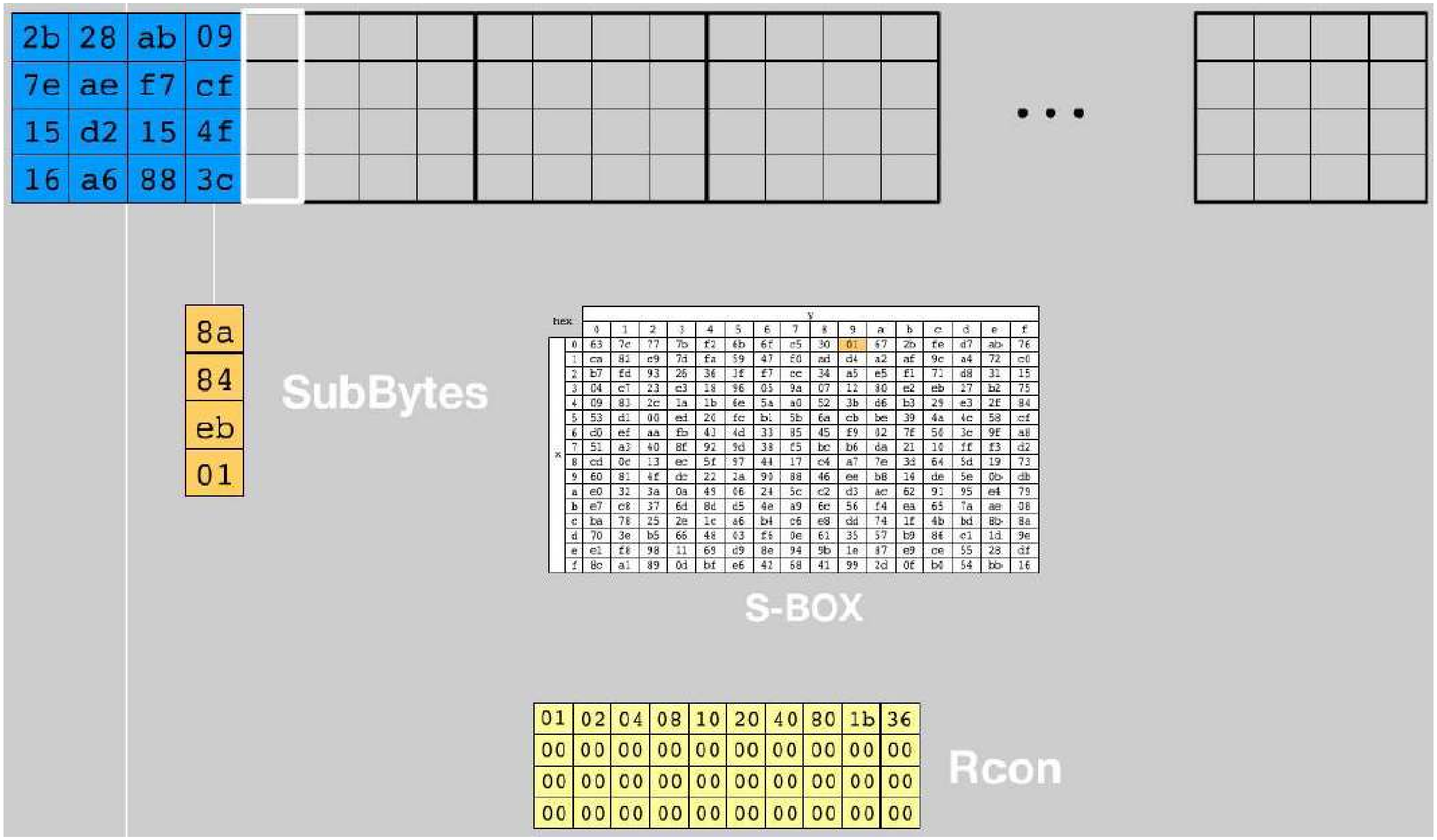
AES Key Expansion Example (contd)



AES Key Expansion Example (contd)



AES Key Expansion Example (contd)

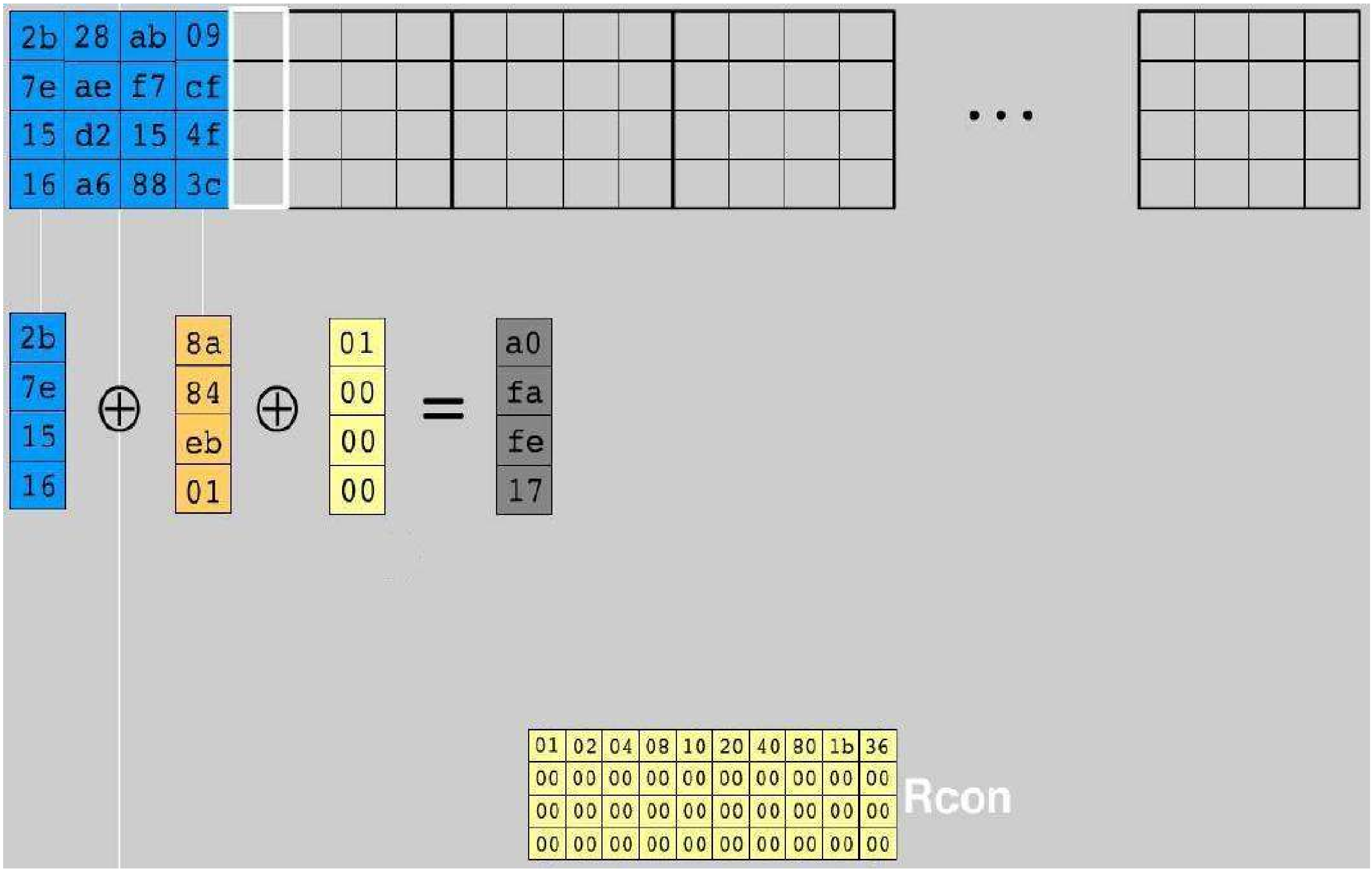


2b	28	ab	09
7e	ae	f7	cf
15	d2	15	4f
16	a6	88	3c

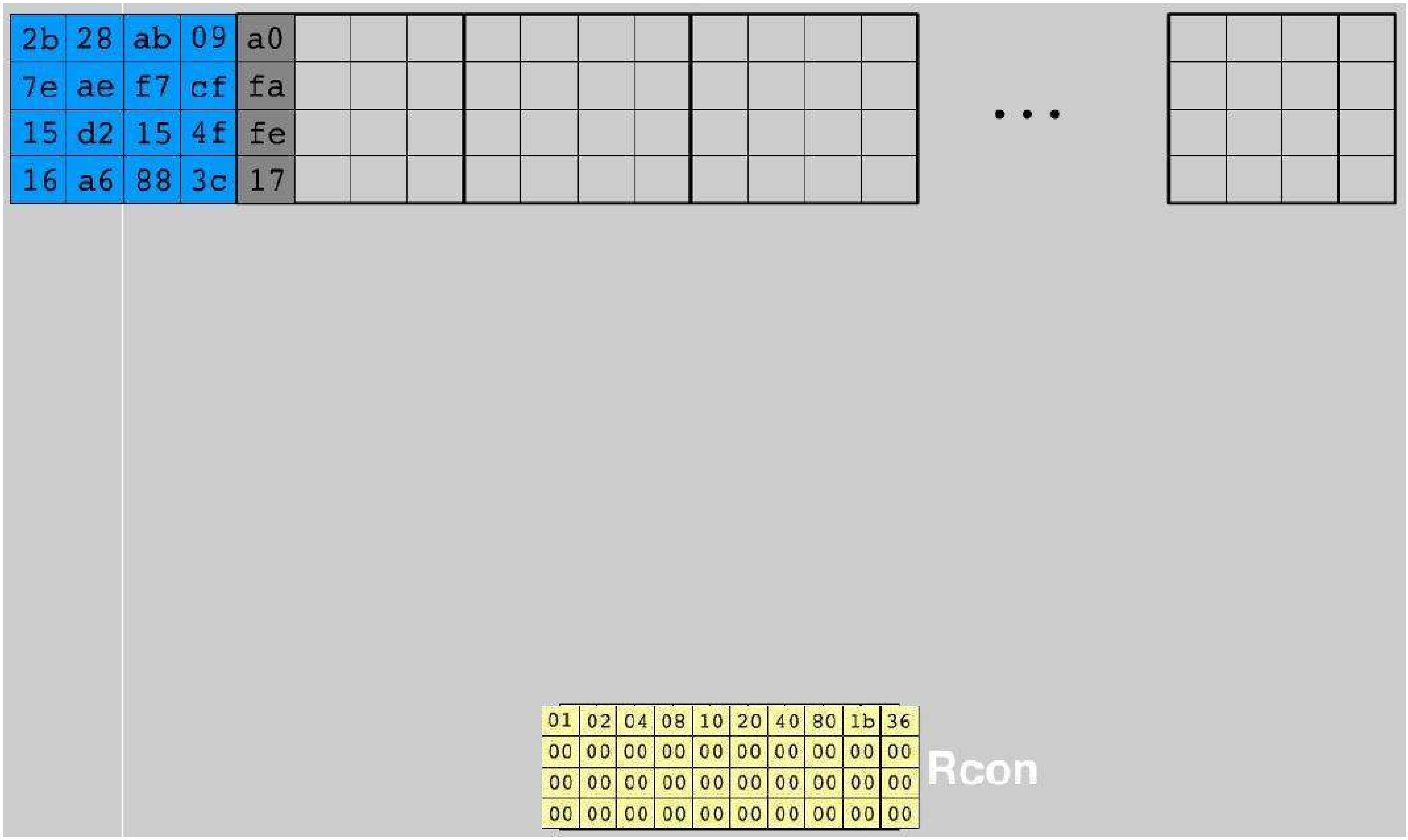
hex	0	1	2	3	4	5	6	7	8	9	a	b	c	d	e	f
0	63	7c	77	7b	f2	6b	6f	c5	30	01	67	2b	fe	d7	ab	76
1	ca	82	c9	7d	fa	59	47	f0	ad	d4	a2	af	9c	a4	72	c0
2	b7	fd	93	26	36	3f	f7	cc	34	a5	e5	f1	71	d8	31	15
3	04	c7	23	c3	18	96	05	9a	07	12	80	e2	eb	27	b2	75
4	09	83	2c	1a	1b	6e	5a	a0	52	3b	d6	b3	29	e3	2f	84
5	53	d1	00	ed	20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

01	02	04	08	10	20	40	80	1b	36
00	00	00	00	00	00	00	00	00	00
00	00	00	00	00	00	00	00	00	00
00	00	00	00	00	00	00	00	00	00

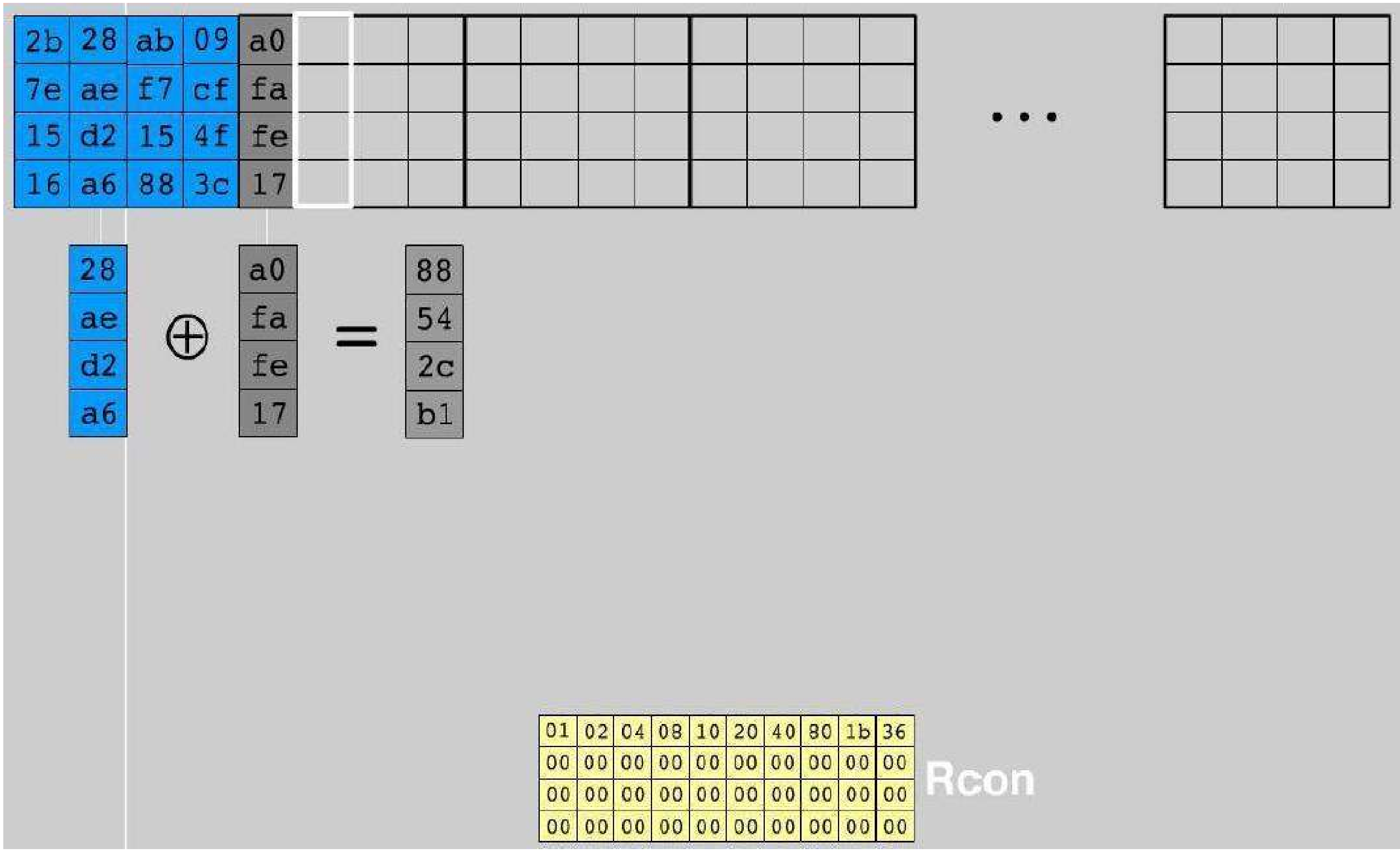
AES Key Expansion Example (contd)



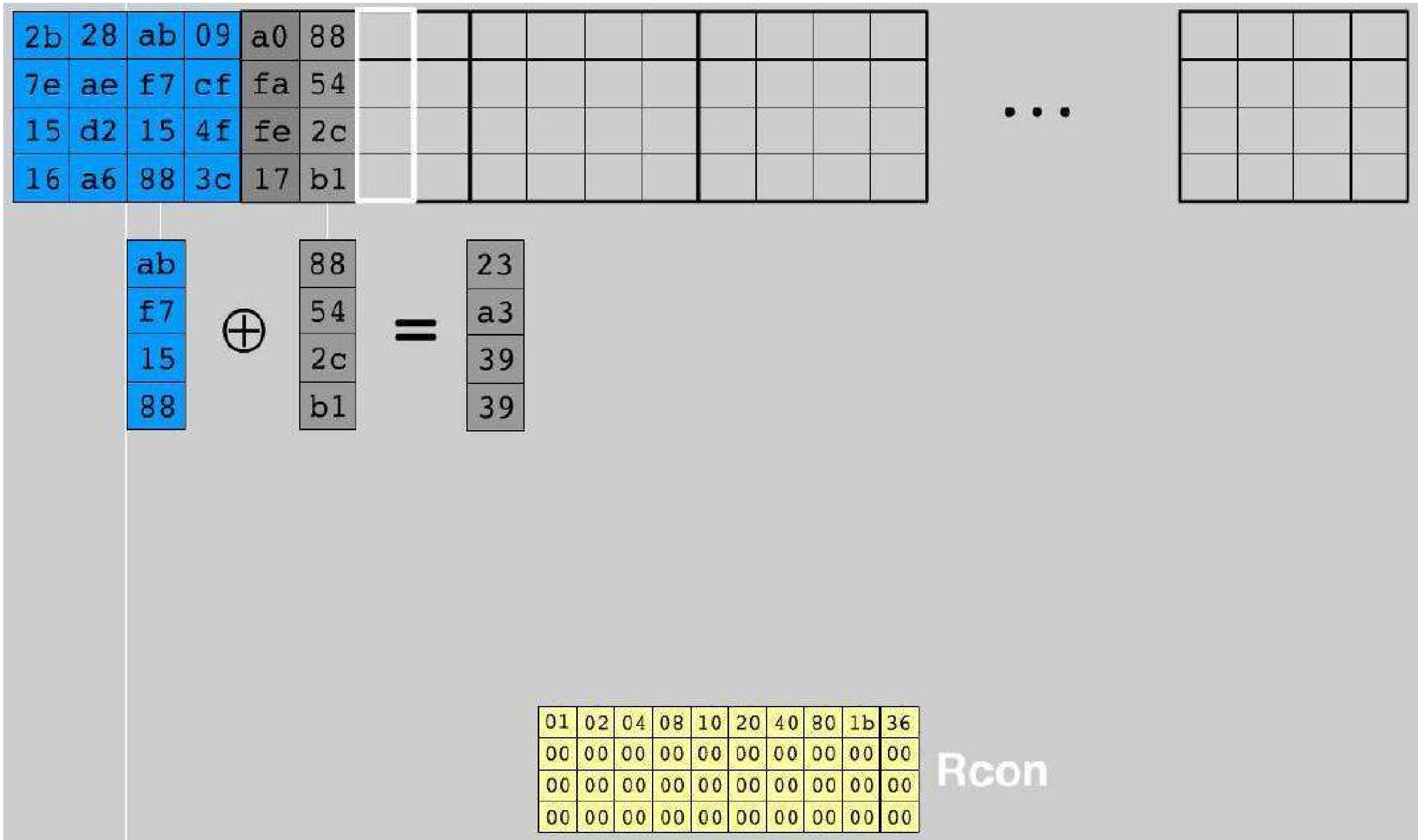
AES Key Expansion Example (contd)



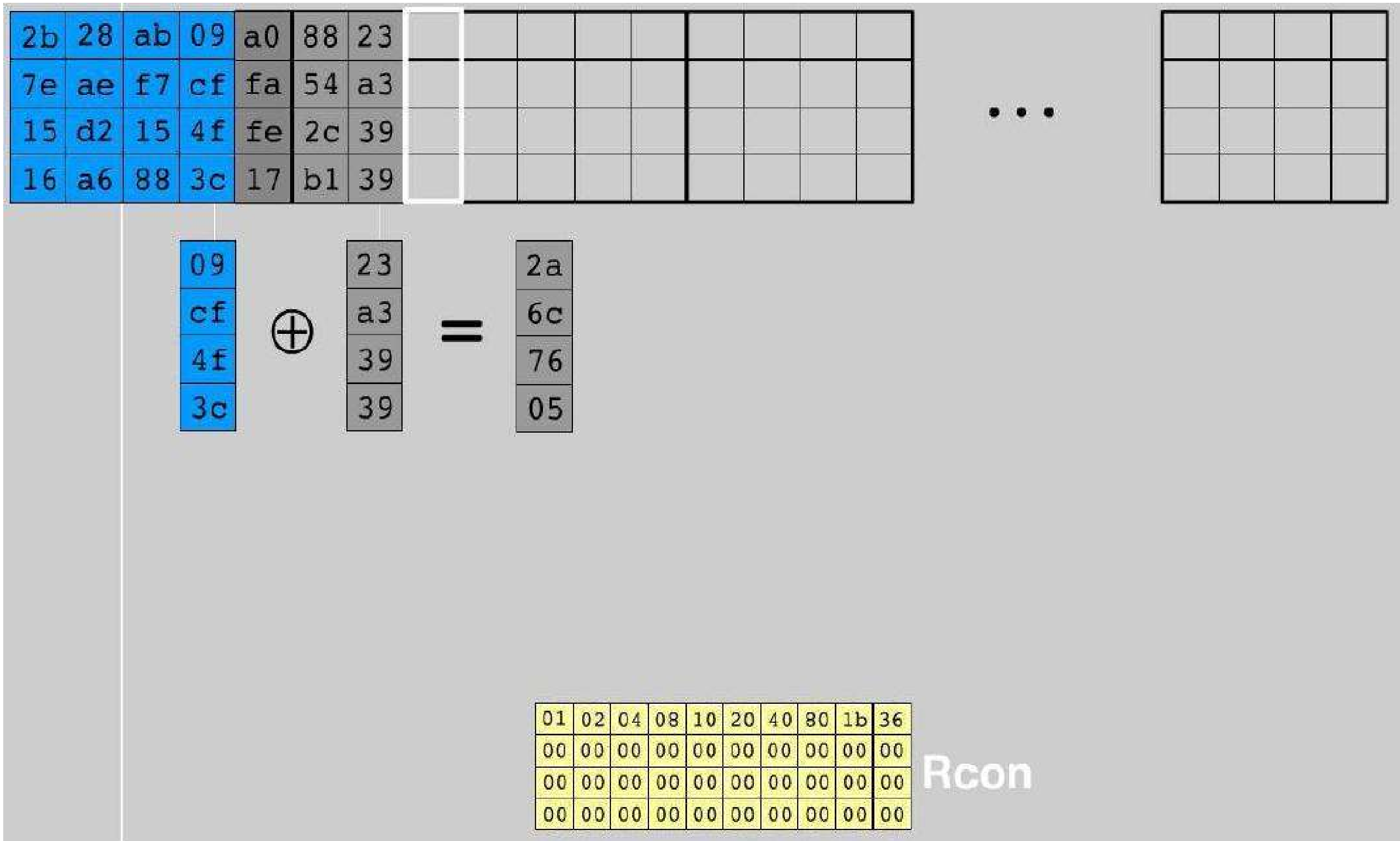
AES Key Expansion Example (contd)



AES Key Expansion Example (contd)



AES Key Expansion Example (contd)



AES Key Expansion Example (contd)

Cipher Key				Round key 1				Round key 2				Round key 3					Round key 10			
2b	28	ab	09	a0	88	23	2a	f2	7a	23	73	3d	47	1e	6d		d0	c9	e1	b6
7e	ae	f7	cf	fa	54	a3	6c	c2	96	a3	59	80	16	23	7a	• • •	14	ee	3f	63
15	d2	15	4f	fe	2c	39	76	95	b9	39	f6	47	fe	7e	88		f9	25	0c	0c
16	a6	88	3c	17	b1	39	05	f2	43	39	7f	7d	3e	44	3b		a8	89	c8	a6

Initial Round for Encryption

Input Data Block

32	88	31	e0
43	5a	31	37
f6	30	98	07
a8	8d	a2	34

$\oplus$

Cipher Key

2b	28	ab	09
7e	ae	f7	cf
15	d2	15	4f
16	a6	88	3c

=

Input for 1st Round

19	a0	9a	e9
3d	f4	c6	f8
e3	e2	8d	48
be	2b	2a	08

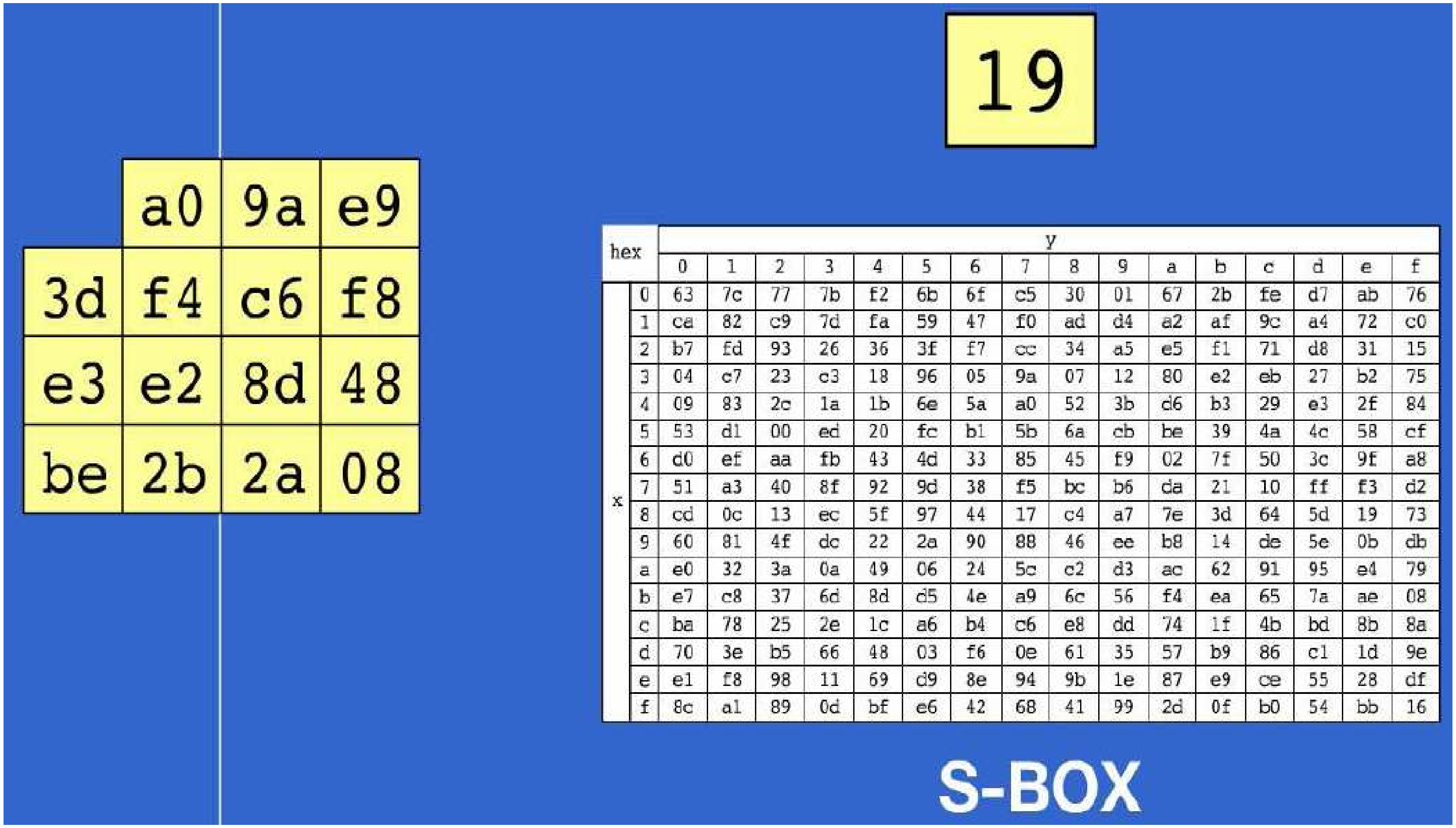
1stRound - SubBytes transformation

19	a0	9a	e9
3d	f4	c6	f8
e3	e2	8d	48
be	2b	2a	08

hex		y															
		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
x	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

S-BOX

1st Round - SubBytes transformation (contd)



hex	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

1st Round - SubBytes transformation (contd)

19

	a0	9a	e9
3d	f4	c6	f8
e3	e2	8d	48
be	2b	2a	08

hex		y															
		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
x	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

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1^{st} Round - SubBytes transformation (contd)

d4	a0	9a	e9
3d	f4	c6	f8
e3	e2	8d	48
be	2b	2a	08

hex		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

S-BOX

1st Round - SubBytes transformation (contd)

Result after SubBytes stage

d4	e0	b8	1e
27	bf	b4	41
11	98	5d	52
ae	f1	e5	30

hex		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

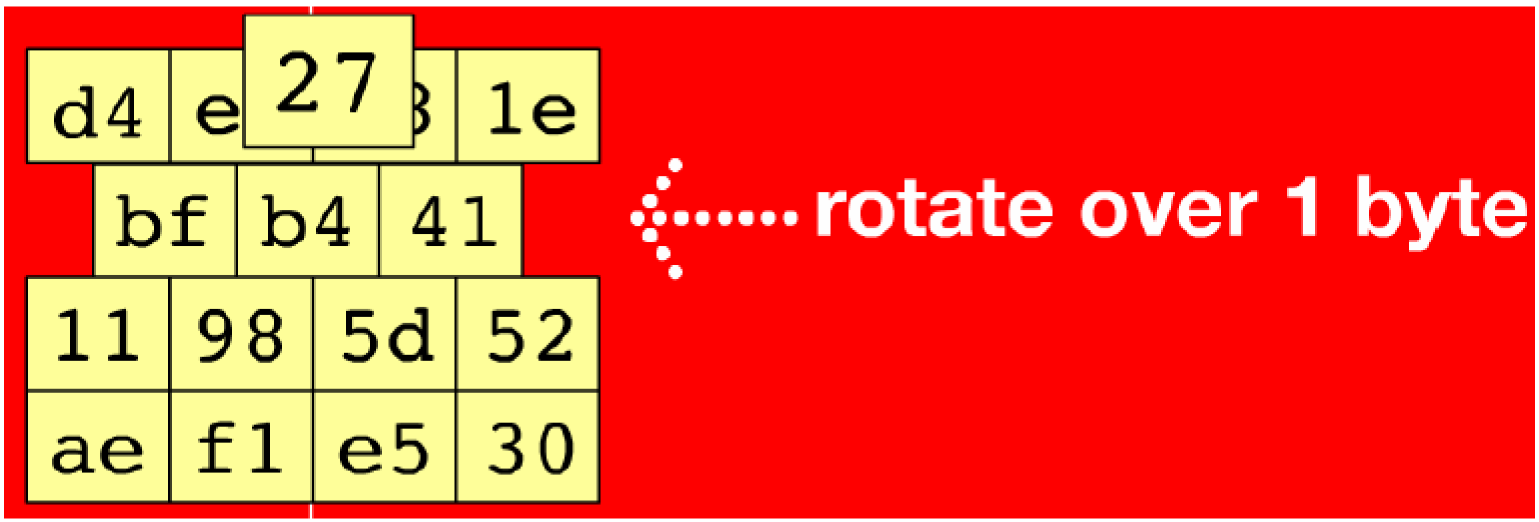
S-BOX

1st Round – ShiftRows transformation

d4	e0	b8	1e
27	bf	b4	41
11	98	5d	52
ae	f1	e5	30

rotate over 1 byte

1st Round – ShiftRows transformation (contd)



1st Round – ShiftRows transformation (contd)

d4	e0	b8	1e
bf	b4	41	27
11	98	5d	52
ae	f1	e5	30

rotate over 1 byte

1st Round – ShiftRows transformation (contd)

d4	e0	b8	1e
bf	b4	41	27
11	98	5d	52
ae	f1	e5	30

rotate over 2 bytes

1st Round – ShiftRows transformation (contd)

d4	e0	b8	1e
bf	b4	41	27
5d	52	11	98
ae	f1	e5	30

rotate over 2 bytes

1st Round – ShiftRows transformation (contd)

d4	e0	b8	1e
bf	b4	41	27
5d	52	11	98
ae	f1	e5	30

rotate over 3 bytes

1st Round – ShiftRows transformation (contd)

Result after ShiftRows stage

d4	e0	b8	1e
bf	b4	41	27
5d	52	11	98
30	ae	f1	e5

rotate over 3 bytes

1^{st} Round – MixColumns transformation

e0	b8	1e
b4	41	27
52	11	98
ae	f1	e5

$$\begin{bmatrix} d4 \\ bf \\ 5d \\ 30 \end{bmatrix} \bullet \begin{bmatrix} 02 & 03 & 01 & 01 \\ 01 & 02 & 03 & 01 \\ 01 & 01 & 02 & 03 \\ 03 & 01 & 01 & 02 \end{bmatrix} = \begin{bmatrix} 04 \\ 66 \\ 81 \\ e5 \end{bmatrix}$$

1^{st} Round– MixColumns transformation

$$\begin{bmatrix} d4 \\ bf \\ 5d \\ 30 \end{bmatrix} \bullet \quad [\ 02 \ \ 03 \ \ 01 \ \ 01\ ]$$

$$=(\{d4\}\bullet\{02\}) \oplus (\{bf\}\bullet\{03\}) \oplus (\{5d\}\bullet\{01\}) \oplus (\{30\} \bullet \{01\})$$

$$=04 = s'_{0,0}$$

Multiplication in GF (2^8)

1st Round – MixColumns transformation

Result after MixColumns transforamtion

04	e0	48	28
66	cb	f8	06
81	19	d3	26
e5	9a	7a	4c

1st Round – AddRound Key

Input for this stage

04	e0	48	28
66	cb	f8	06
81	19	d3	26
e5	9a	7a	4c

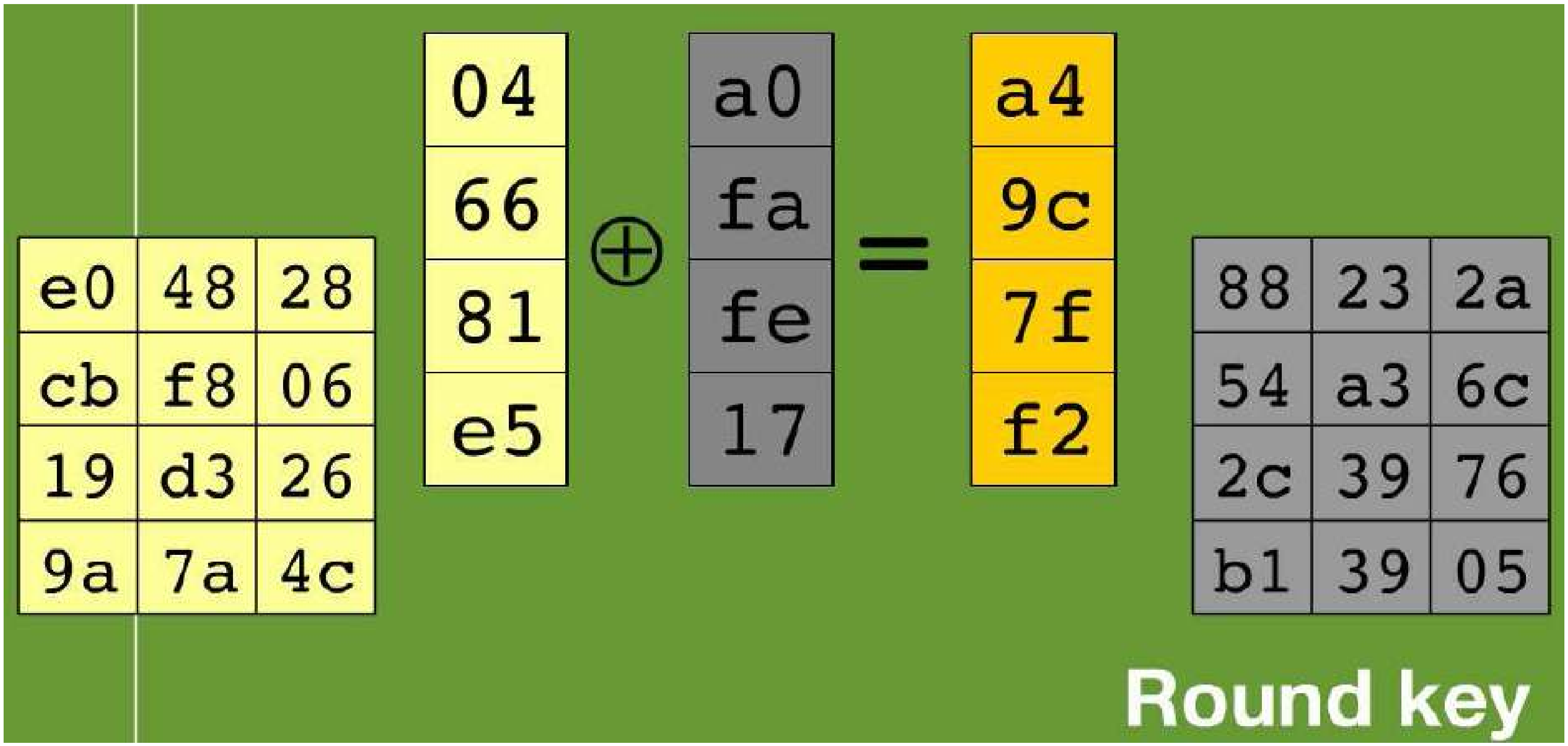
1st Round – AddRound Key (contd)

04	e0	48	28
66	cb	f8	06
81	19	d3	26
e5	9a	7a	4c

a0	88	23	2a
fa	54	a3	6c
fe	2c	39	76
17	b1	39	05

Round key

1^{st} Round – AddRound Key Example (contd)



1st Round – AddRound Key Example (contd)

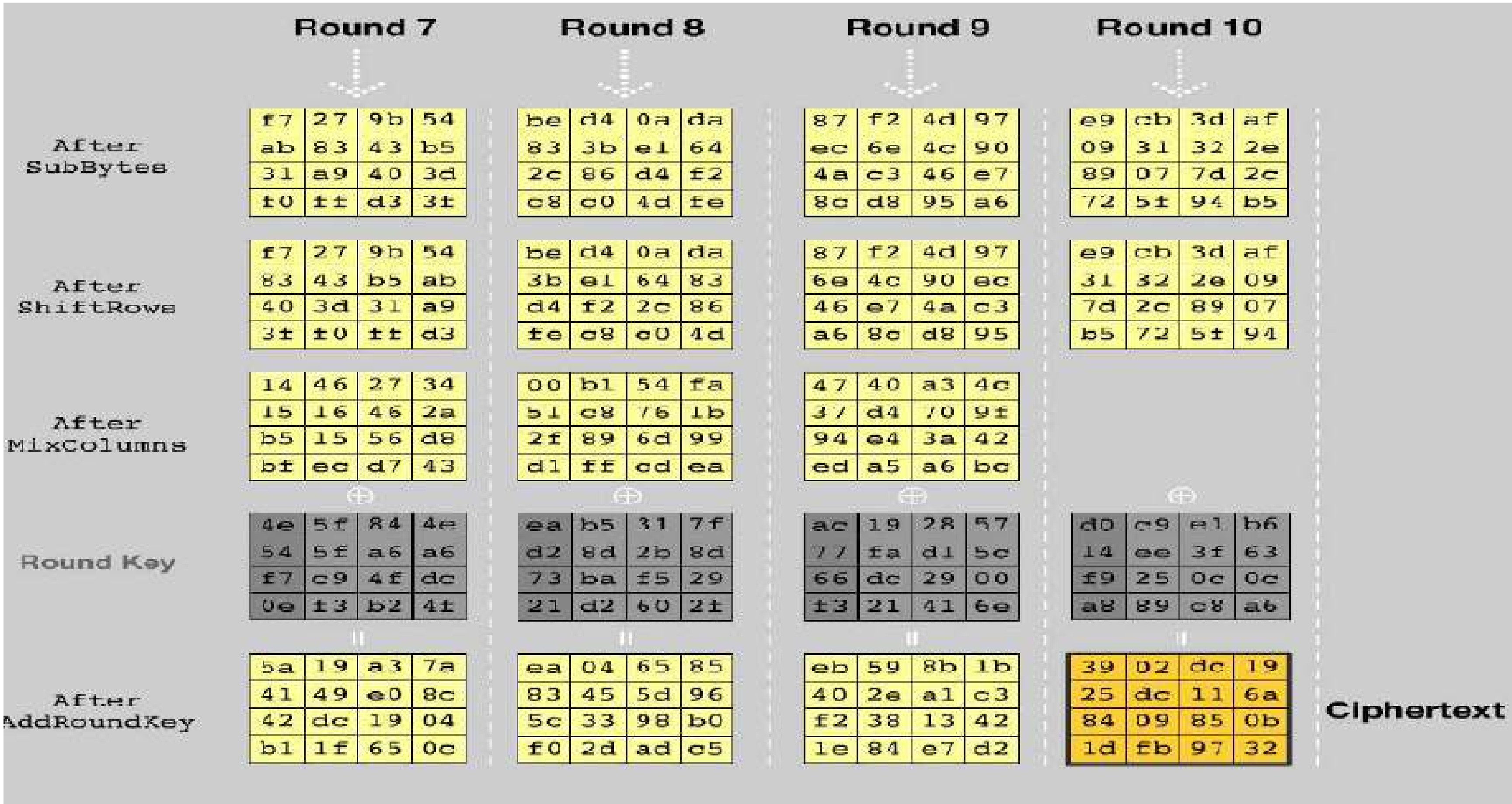
a4	68	6b	02
9c	9f	5b	6a
7f	35	ea	50
f2	2b	43	49

Round key

Results for remaining rounds

	Round 2	Round 3	Round 4	Round 5	Round 6
After SubBytes	49 45 7f 77	ac ef 13 45	52 85 e3 f6	e1 e8 35 97	a1 78 10 4c
	de db 39 02	73 c1 b5 23	50 a4 11 cf	4f fb c8 6c	63 4f e8 d5
	d2 96 87 53	cf 11 d6 5a	2f 5e c8 6a	d2 fb 96 ae	a8 29 3d 03
	89 f1 1a 3b	7b df b5 b8	28 d7 07 94	9b ba 53 7c	fc df 23 fe
After ShiftRows	49 45 7f 77	ac ef 13 45	52 85 e3 f6	e1 e8 35 97	a1 78 10 4c
	db 39 02 de	c1 b5 23 73	a4 11 cf 50	fb c8 6c 4f	4f e8 d5 63
	87 53 d2 96	d6 5a cf 11	c8 6a 2f 5e	96 ae d2 fb	3d 03 a8 29
	3b 89 f1 1a	b8 7b df b5	94 28 d7 07	7c 9b ba 53	fe fc df 23
After MixColumns	58 1b db 1b	75 20 53 bb	0f 60 6f 5e	25 bd b6 4c	4b 2c 33 37
	4d 4b e7 6b	ec 0b c0 25	d6 31 c0 b3	d1 11 3a 4c	86 4a 9d d2
	ca 5a ca b0	09 63 cf d0	da 38 10 13	a9 d1 33 c0	8d 89 f4 18
	f1 ac a8 e5	93 33 7c dc	a9 bf 6b 01	ad 68 8e b0	6d 80 e8 d8
⊕ Round Key	f2 7a 59 73	3d 47 1e 6d	ef a8 b6 db	d4 7c ca 11	6d 11 db ca
	c2 96 35 59	80 16 23 7a	44 52 71 0b	d1 83 f2 f9	88 0b f9 00
	95 b9 80 f6	47 fe 7e 88	a5 5b 25 ad	c6 9d b8 15	a3 3e 86 93
	f2 43 7a 7f	7d 3e 44 3b	41 7f 3b 00	f8 87 bc bc	7a fd 41 fd
= After AddRoundKey	aa 61 82 68	48 67 4d d6	e0 c8 d9 85	f1 c1 7c 5d	26 3d e8 fd
	8f dd d2 32	6c 1d e3 5f	92 63 b1 b8	00 92 c8 b5	0e 41 64 d2
	5f e3 4a 46	4e 9d b1 58	7f 63 35 be	6f 4c 8b d5	2e b7 72 8b
	03 ef d2 9a	ee 0d 38 e7	e8 c0 50 01	55 ef 32 0c	17 7d a9 25

Results for remaining rounds



Pseudo code for the Inverse Cipher

```
EqInvCipher(byte in[4 * Nb], byte out[4 * Nb], word dw[Nb * (Nr + 1)])
begin
   byte  state[4,Nb]

   state = in

   AddRoundKey(state, dw + Nr * Nb)

   for round = Nr - 1 step -1 to 1
      InvSubBytes(state)
      InvShiftRows(state)
      InvMixColumns(state)
      AddRoundKey(state, dw + round * Nb)
   end for

   InvSubBytes(state)
   InvShiftRows(state)
   AddRoundKey(state, dw)

   out = state
end
```

Implementation Issues

- **Key Length Requirements**
  - An implementation of the AES algorithm shall support *at least one* of the three key lengths: 128, 192, or 256 bits (i.e., ***Nk*** = 4, 6, or 8, respectively).
  - Implementations may optionally support two or three key lengths, which may promote the interoperability of algorithm implementations.
- **Keying Restrictions**
  - No weak or semi-weak keys have been identified for the AES algorithm, and there is no restriction on key selection.
- **Parameterization of Key Length, Block Size, and Round Number**
  - This standard explicitly defines the allowed values for the key length (N_k), block size (N_b), and number of rounds (N_r).
  - However, future reaffirmations of this standard could include changes or additions to the allowed values for those parameters. Therefore, implementers may choose to design their AES implementations with future flexibility in mind.

Calculation of Rcon

- Rcon(i) = 02 • Rcon(i-1)   where i is round number
- Rcon(1) = 01
  - So, Rcon used for 1st round is [01 00 00 00] word.
- Rcon(2) = 02 • Rcon(1)

  = 02 • 01 = 02
  - So, Rcon used for 2nd round is [02 00 00 00] word.
- Rcon(3) = 02 • Rcon(2)

  = 02 • 02 = 04
  - So, Rcon used for 3rd round is [02 00 00 00] word.
- Similarly Rcon(4) = 08

  Rcon(5) = 10

  Rcon(6) = 20

  Rcon(7) = 40

  Rcon(8) = 80

  Rcon(9) = 1B

  Rcon(10) = 36

Back