CYB 241 Digital Cryptography Techniques

Advanced Encryption Standard (AES)

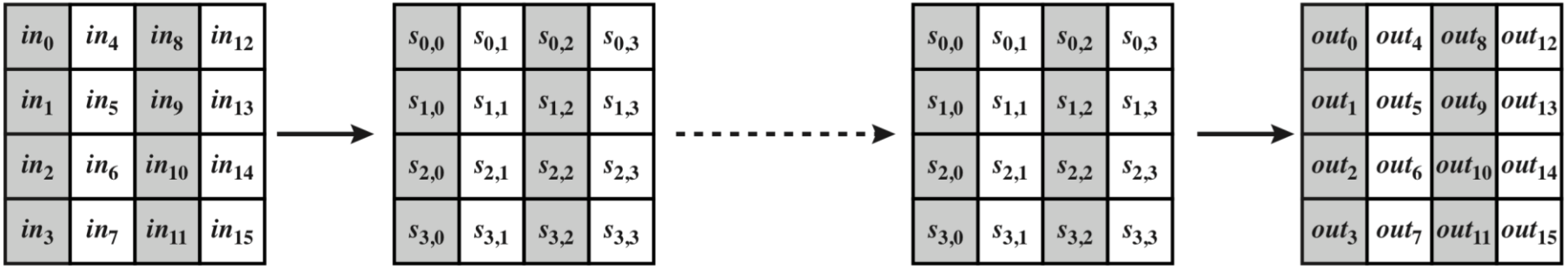
AES General Structure

- Key length: 128, 192, or 256 bits
  - AES-128, AES-192, or AES-256, accordingly
- Plaintext block: 128 bits (16 bytes)
- Depicted as 4×4 matrix of bytes (by column)
- Copied into State array
- Modified at each stage encrypt / decrypt
- Copied to output matrix after final stage

AES General Structure

- AES Cipher consists of N-rounds
  - 10, 12, or 14, depending on key length
- Rounds 1 to N – 1 consist of four transforms
- Each transform takes 4×4 matrix in
  - Produces 4×4 matrix out
- Output of final round is the ciphertext
- Key expansion generations N + 1 round keys
- Each round key is 4×4 matrix (w)

AES Data Structures



(a) Input, state array, and output

(b) Key and expanded key

Figure 5.2 AES Data Structures

AES Parameters

Key Size (words/bytes/bits)	4/16/128	6/24/192	8/32/256
Plaintext Block Size (words/bytes/bits)	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

AES Transformation Functions

- Substitute Bytes
- Shift Rows
- Mix Columns
- Add Round Key

AES Encryption and Decryption

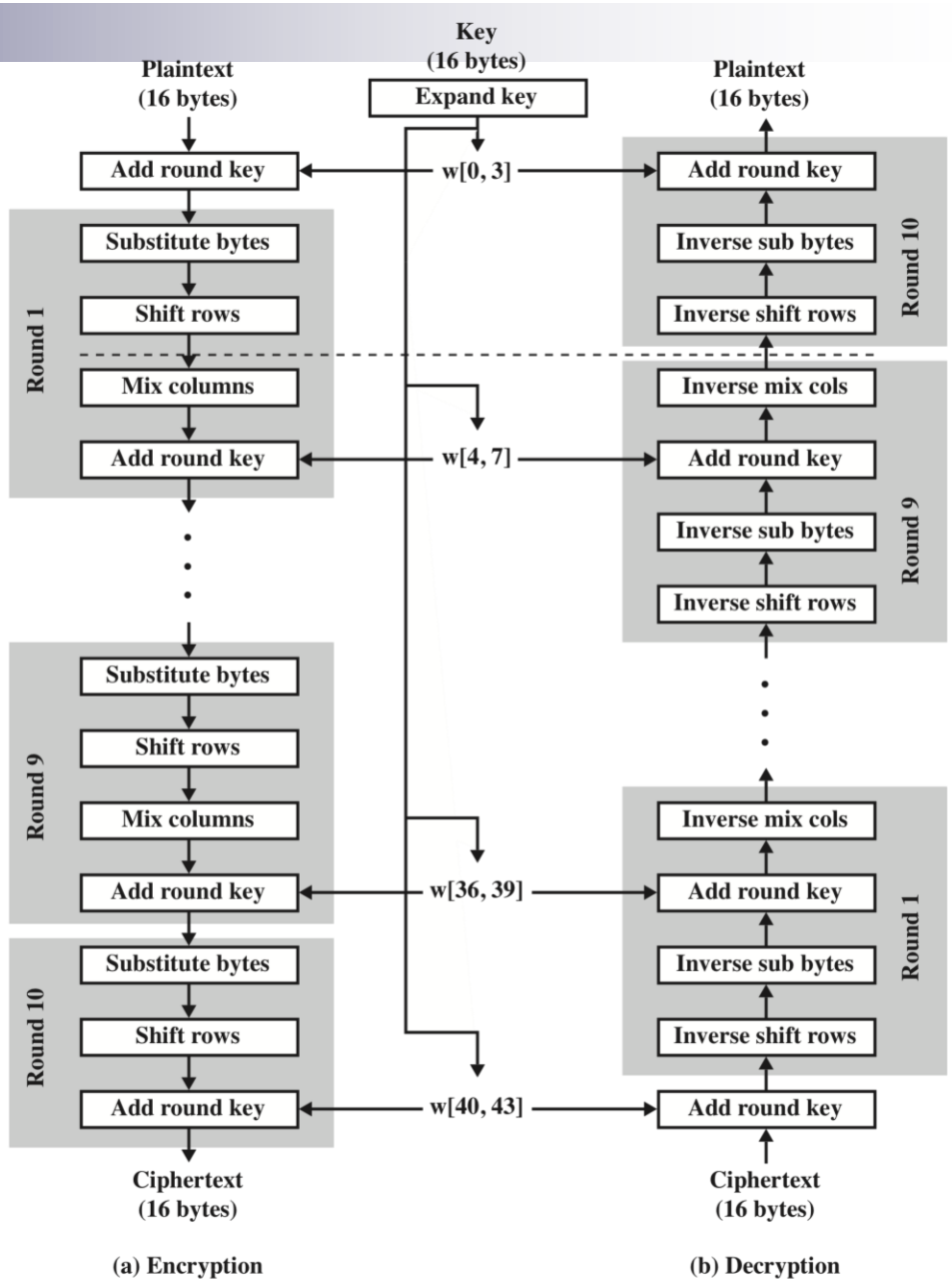
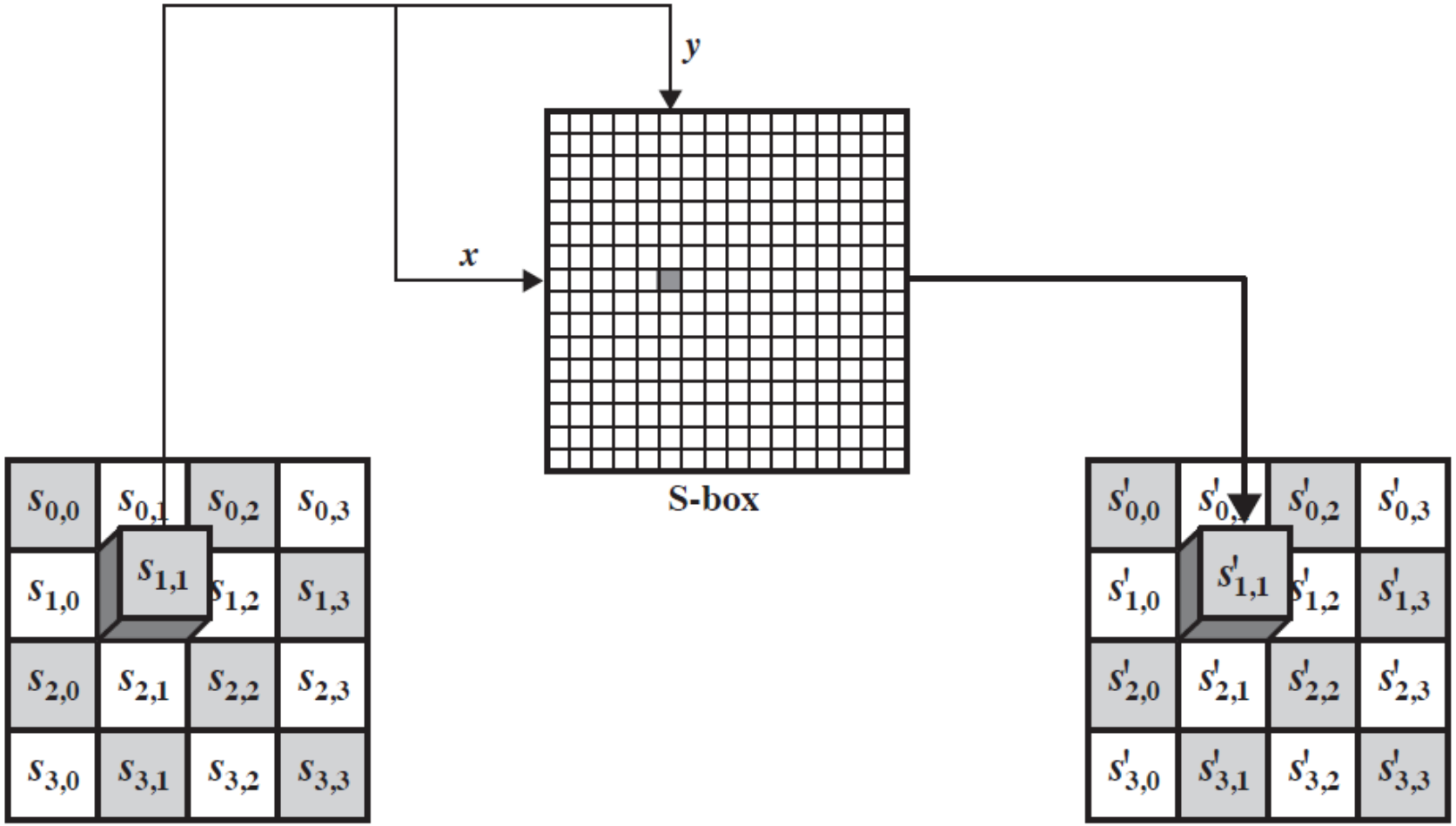


Figure 5.3 AES Encryption and Decryption

Substitute Bytes Transformation

- Simple table lookup
- Uses AES S-box
  - contains all possible 256 8-bit permutations
- Each byte in State maps to new byte
  - leftmost 4 bits used as row
  - rightmost 4 bits used for column

Substitute Bytes Transformation



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

		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

Example

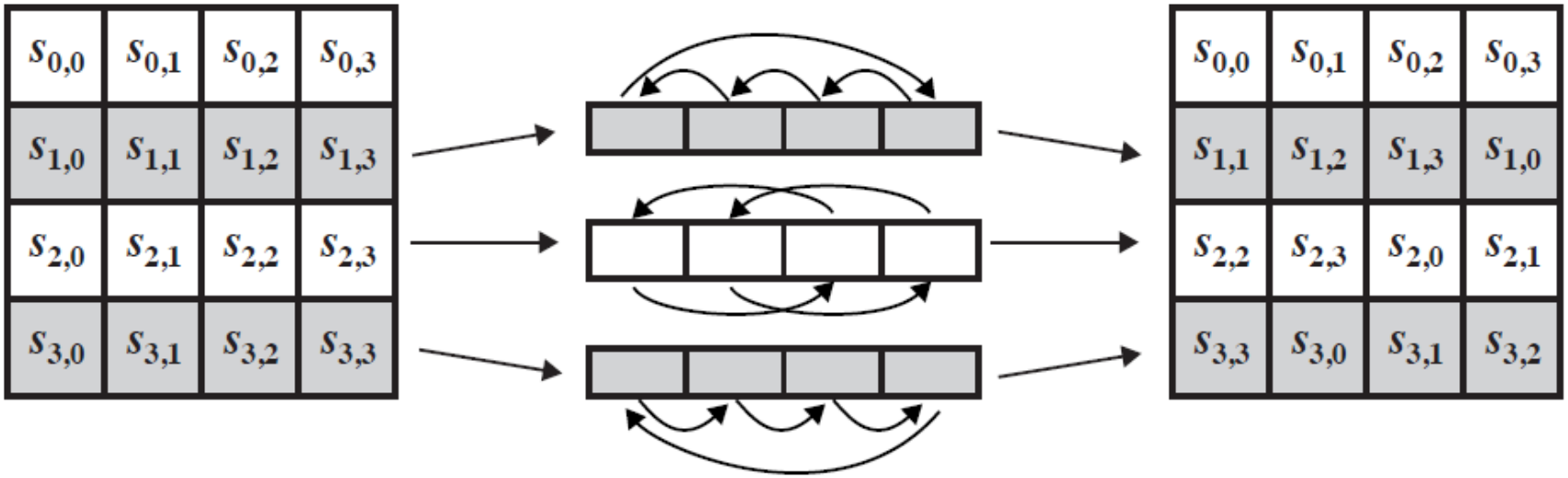
EA	04	65	85
83	45	5D	96
5C	33	98	B0
F0	2D	AD	C5

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

ShiftRows Transformation

- First row not altered
- Second row 1-byte circular left shift
- Third row 2-byte circular left shift
- Fourth row 3-byte circular left shift
- In inverse transformation (InvShiftRows)
  - circular shifts done in opposite direction
- Spread 4 bytes of one column to all columns

ShiftRows Transformation



Example

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

MixColumns Transformation

- Operates on each column individually
- Each byte of a column mapped to new value
  - function of all bytes in that column

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

MixColumns Transformation

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

Example

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

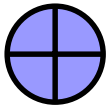
47	40	A3	4C
37	D4	70	9F
94	E4	3A	42
ED	A5	A6	BC

AddRoundKey Transformation

- 128 bits of State XORed with round key
- Inverse AddRoundKey is the same
- Rationale
  - as simple as possible
  - affects all bits of State
  - Complexity of round key expansion + complexity of other stages of AES, ensures security

Example

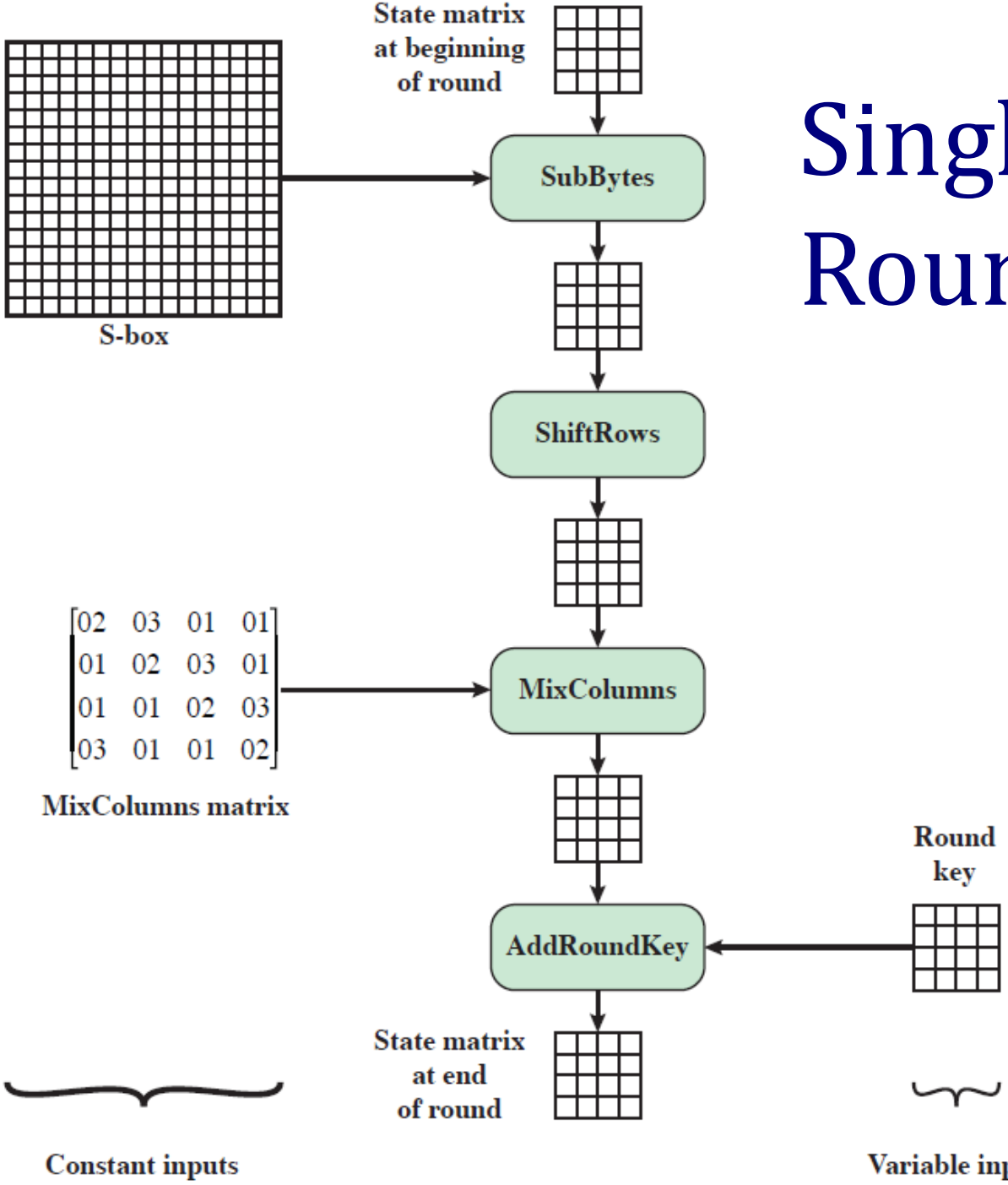
47	40	A3	4C
37	D4	70	9F
94	E4	3A	42
ED	A5	A6	BC



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

Single AES Round



AES Key Expansion

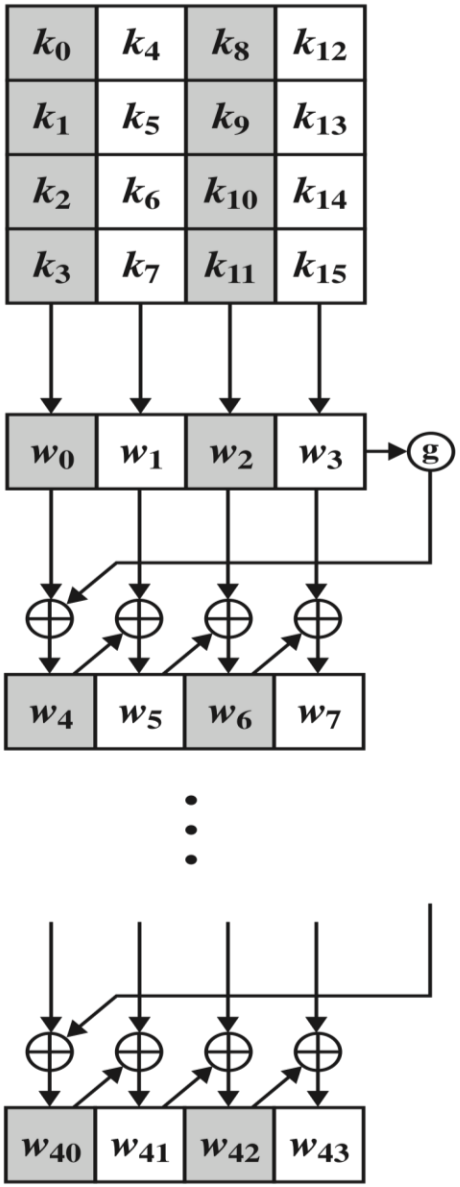
- Takes 4-word (16 bytes) as input and produces array of 44 words (176 bytes)
- Provide 4-word round keys for
  - initial **AddRoundKey** stage
  - other 10 rounds
- Key is copied into the first four words of the expanded key
- Each added word *w*[i] depends on the immediately preceding word, *w[i – 1],* and the word four positions back, w[i – 4]
  - In three out of four cases a simple XOR is used
  - For a word whose position in the *w* array is a multiple of 4, a more complex function is used

AES Key Expansion

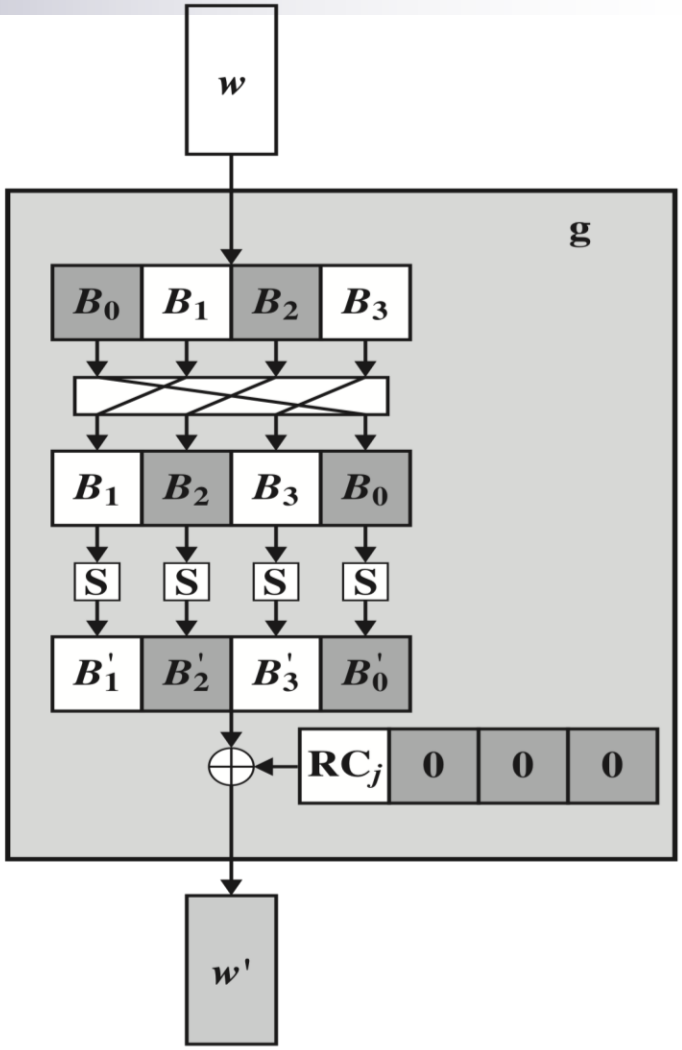
- RotWord
  - one-byte circular left shift on a word
  - $[B_0, B_1, B_2, B_3] \rightarrow [B_1, B_2, B_3, B_0]$
- SubWord
  - byte substitution on each byte of a word
  - using S-box
- Rcon[j] = (RC[j], 0, 0, 0)

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

AES Key Expansion



(a) Overall algorithm



(b) Function g

Figure 5.9 AES Key Expansion

Example

Key	0f 15 71 c9 47 d9 e8 59 0c b7 ad df af 7f 67 98

Key Words	Auxiliary Function
w0 = 0f 15 71 c9 w1 = 47 d9 e8 59 w2 = 0c b7 ad df w3 = af 7f 67 98	RotWord(w3) = 7f 67 98 af = x1 SubWord(x1) = d2 85 46 79 = y1 Rcon(1) = 01 00 00 00 y1 ⊕ Rcon(1)= d3 85 46 79 = z1
w4 = w0 ⊕ z1 = dc 90 37 b0 w5 = w4 ⊕ w1 = 9b 49 df e9 w6 = w5 ⊕ w2 = 97 fe 72 3f w7 = w6 ⊕ w3 = 38 81 15 a7	RotWord(w7) = 81 15 a7 38 = x2 SubWord(x2) = 0c 59 5c 07 = y2 Rcon(2) = 02 00 00 00 y2 ⊕ Rcon(2)= 0e 59 5c 07 = z2
w8 = w4 ⊕ z2 = d2 c9 6b b7 w9 = w8 ⊕ w5 = 49 80 b4 5e w10 = w9 ⊕ w6 = de 7e c6 61 w11 = w10 ⊕ w7 = e6 ff d3 c6	RotWord(w11)= ff d3 c6 e6 = x3 SubWord(x3) = 16 66 b4 8e = y3 Rcon(3) = 04 00 00 00 y3 ⊕ Rcon(3)= 12 66 b4 8e = z3

AES Encryption Cipher Overview

- Youtube Example
  - https://www.youtube.com/watch?v=H2LlHOw_ANg

Reading Assignment

- Textbook
  - chapter 6
    - 6.2, 6.3, 6.4, 6.5