CENG 471 Cryptography

Symmetrical Cryptosystems

Advanced Encryption Standard (AES)

Asst. Prof. Dr. Serap ŞAHİN Izmir Institute of Technology

Reference: Slides of B.Forouzan, "Cryptography and Network Security"

Objectives

- To review a short history of AES
- •To define the basic structure of AES
- •To define the transformations used by AES
- •To define the key expansion process
- Security and Implementation

INTRODUCTION

The Advanced Encryption Standard (AES) is a symmetric-key block cipher published by the National Institute of Standards and Technology (NIST) in December 2001.

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.

Criteria

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

- 1. Security
- 2. Cost
- 3. Implementation.

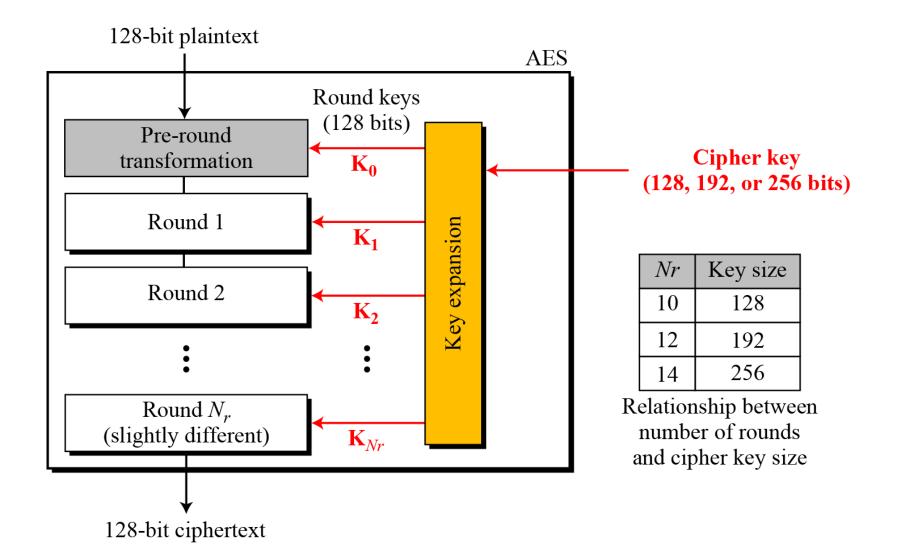
Rounds

AES is a **non-Feistel cipher** that encrypts and decrypts a **data block of 128 bits**. It uses 10, 12, or 14 rounds. The key size, which can be 128, 192, or 256 bits, depends on the number of rounds.

AES has defined three versions, with 10, 12, and 14 rounds.

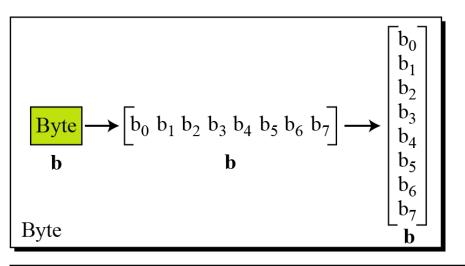
Each version uses a different cipher key size (128, 192, or 256), but the **round keys are always 128 bits**.

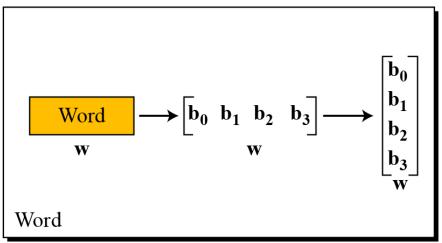
General design of AES encryption cipher



Data Units

Data units used in AES

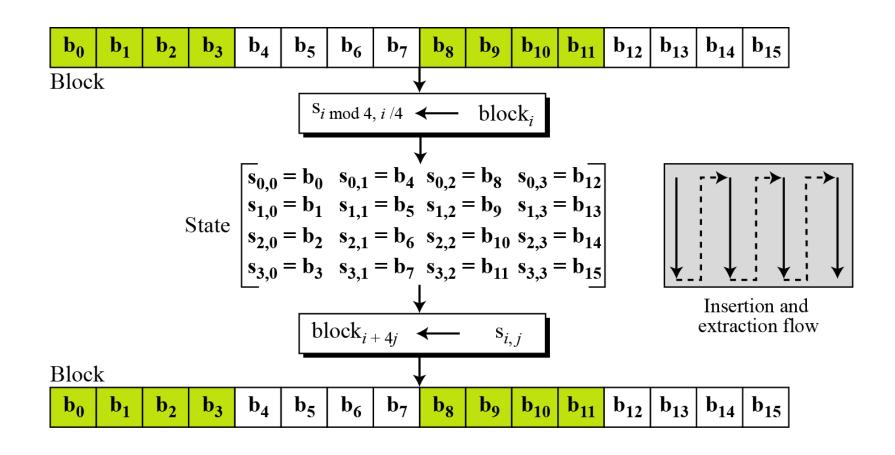




$$S \longrightarrow \begin{bmatrix} s_{0,0} & s_{0,1} & s_{0,2} & s_{0,3} \\ s_{1,0} & s_{1,1} & s_{1,2} & s_{1,3} \\ s_{2,0} & s_{2,1} & s_{2,2} & s_{2,3} \\ s_{3,0} & s_{3,1} & s_{3,2} & s_{3,3} \end{bmatrix} \longrightarrow \begin{bmatrix} w_0 & w_1 & w_2 & w_3 \end{bmatrix}$$
State

Data Units

Block-to-state and state-to-block transformation



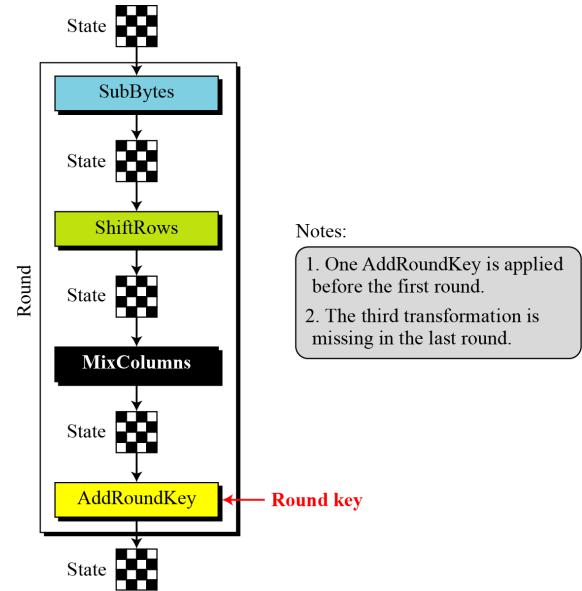
Example 1

Changing plaintext to state

Text	A	Е	S	U	S	Е	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
							Гоо	12	0C	08]						
							04				State					
							12	12	13 11	19	Stat	e				
							<u>_</u> 14	00	11	19						

Structure of Each Round

Structure of each round at the encryption site



TRANSFORMATIONS

To provide security, AES uses four types of transformations:

- substitution,
- permutation,
- mixing, and
- key-adding.

Substitution

AES, like DES, uses substitution. AES uses two invertible transformations.

SubBytes

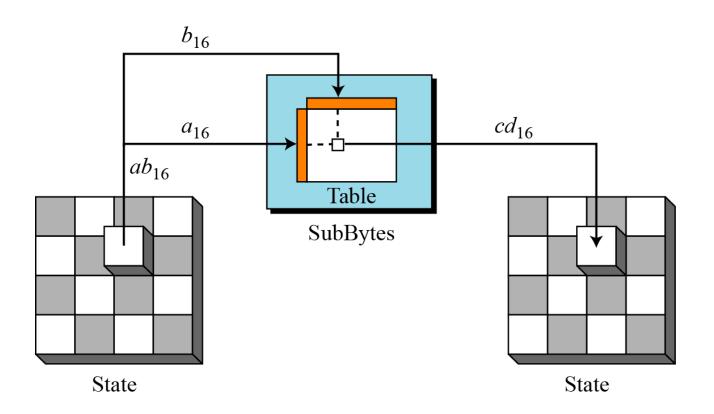
The first transformation, SubBytes, is used at the encryption site. To substitute a byte, we **interpret the byte** as two hexadecimal digits.

1101 0101

d 5

The SubBytes operation involves 16 independent byte-to-byte transformations.

SubBytes transformation



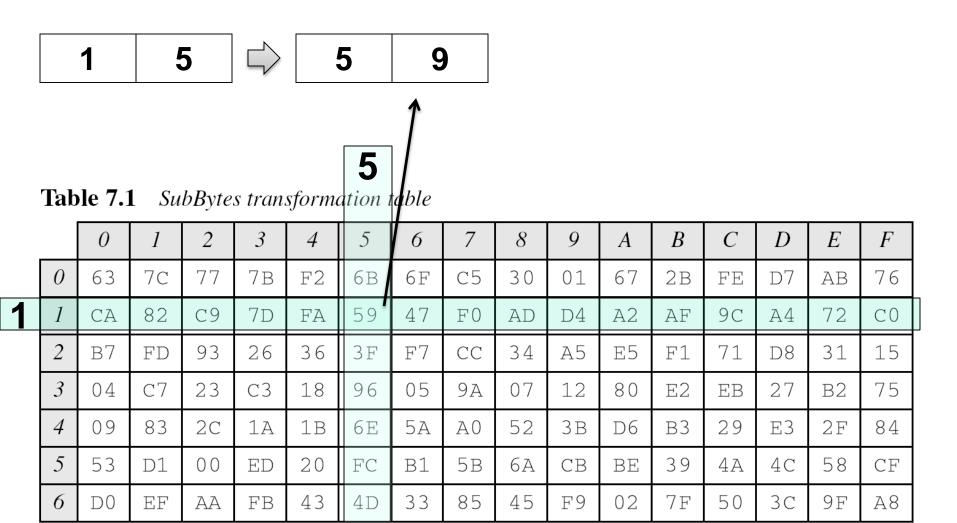


 Table 7.1
 SubBytes transformation table (continued)

	0	1	2	3	4	5	6	7	8	9	A	В	С	D	Е	F
7	51	А3	40	8F	92	9D	38	F5	ВС	В6	DA	21	10	FF	F3	D2
8	CD	0C	13	EC	5F	97	44	17	С4	Α7	7E	3D	64	5D	19	73
9	60	81	4F	DC	22	2A	90	88	46	EE	В8	14	DE	5E	0B	DB
A	ΕO	32	3A	0A	49	06	24	5C	C2	D3	AC	62	91	95	E4	79
В	E7	СВ	37	6D	8D	D5	4E	A9	6C	56	F4	EA	65	7A	ΑE	08
C	ВА	78	25	2E	1C	A6	В4	С6	E8	DD	74	1F	4B	BD	8B	8A
D	70	3 E	В5	66	48	03	F6	ΟE	61	35	57	В9	86	C1	1D	9E
E	E1	F8	98	11	69	D9	8E	94	9В	1E	87	E9	CE	55	28	DF
F	8C	A1	89	0D	BF	E6	42	68	41	99	2D	OF	В0	54	BB	16



InvSubBytes

Table 7.2 InvSubBytes transformation table

	0	1	2	3	4	5	6	7	8	9	A	В	С	D	Е	F
0	52	09	6A	D5	30	36	A5	38	BF	40	А3	9E	81	F3	D7	FB
1	7C	E3	39	82	9В	2F	FF	87	34	8E	43	44	С4	DE	E9	СВ
2	54	7в	94	32	A6	C2	23	3D	EE	1C	95	0B	42	FA	С3	4E
3	08	2E	A1	66	28	D9	24	В2	76	5B	A2	49	6D	8B	D1	25
4	72	F8	F6	64	86	68	98	16	D4	A 4	5C	CC	5D	65	В6	92
5	6C	70	48	50	FD	ED	В9	DA	5E	15	46	57	Α7	8D	9D	84
6	90	D8	AB	00	8C	ВС	D3	0A	F7	E4	58	05	В8	В3	45	06
7	D0	2C	1E	8F	CA	3F	OF	02	C1	AF	BD	03	01	13	8A	6B

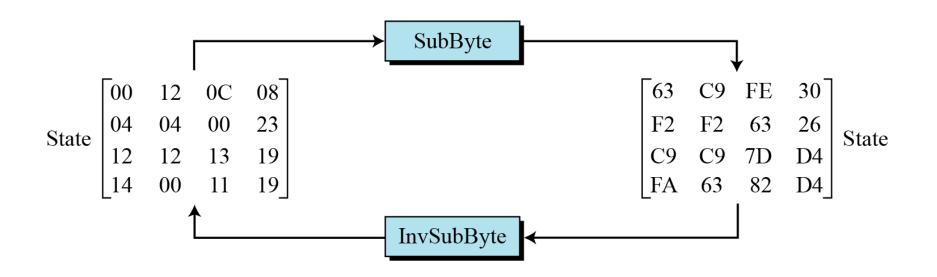
InvSubBytes

	0	1	2	3	4	5	6	7	8	9	A	В	С	D	Ε	F
8	3A	91	11	41	4F	67	DC	EA	97	F2	CF	CE	F0	В4	Е6	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	в7	62	ΟE	AA	18	BE	1B
В	FC	56	3E	4B	C6	D2	79	20	9A	DB	С0	FE	78	CD	5A	F4
C	1F	DD	A8	33	88	07	С7	31	В1	12	10	59	27	80	EC	5F
D	60	51	7F	A9	19	В5	4A	0D	2D	E5	7A	9F	93	С9	9C	EF
E	Α0	ΕO	3B	4D	AE	2A	F5	В0	С8	EB	ВВ	3 C	83	53	99	61
F	17	2В	04	7E	ВА	77	D6	26	E1	69	14	63	55	21	0C	7D

Example 2

Figure 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.

SubBytes transformation for Example 2



Transformation Using the $GF(2^8)$ Field

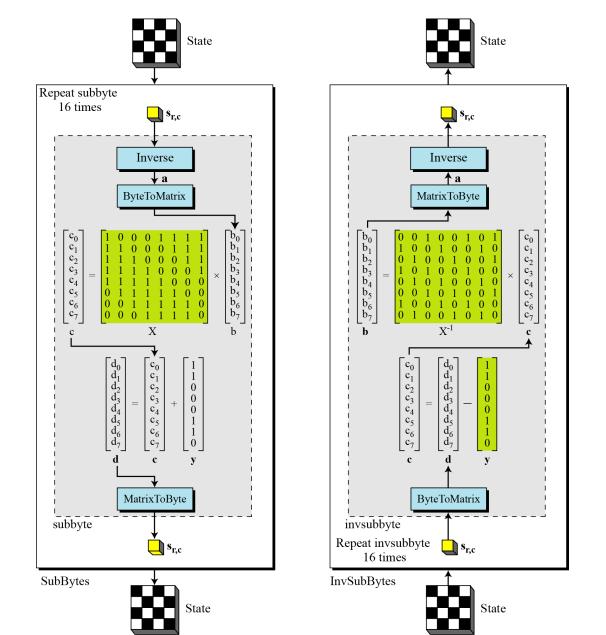
AES also defines the transformation algebraically using the $GF(2^8)$ field with the irreducible polynomials $(x^8 + x^4 + x^3 + x + 1)$.

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

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

The SubBytes and InvSubBytes transformations are inverses of each other.

SubBytes and InvSubBytes processes



Example 3

Let us show how the byte 0C is transformed to FE by subbyte routine and transformed back to 0C by the invsubbyte routine.

1. subbyte:

- a. The multiplicative inverse of 0C in $GF(2^8)$ field is B0, which means **b** is (10110000).
- b. Multiplying matrix **X** by this matrix results in $\mathbf{c} = (10011101)$
- c. The result of XOR operation is $\mathbf{d} = (111111110)$, which is FE in hexadecimal.

2. invsubbyte:

- a. The result of XOR operation is $\mathbf{c} = (10011101)$
- b. The result of multiplying by matrix X^{-1} is (11010000) or B0
- c. The multiplicative inverse of B0 is 0C.

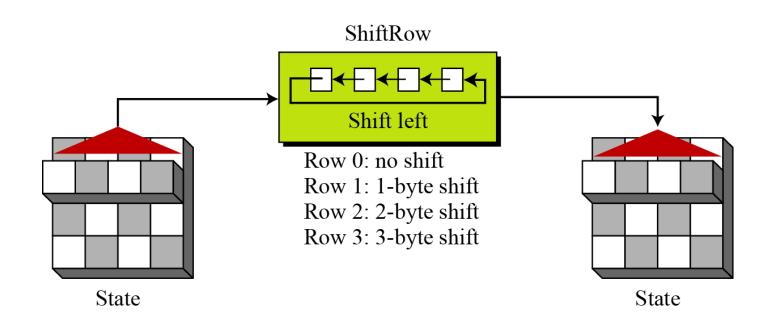
Permutation

Another transformation found in a round is shifting, which permutes the bytes.

ShiftRows

In the encryption, the transformation is called ShiftRows.

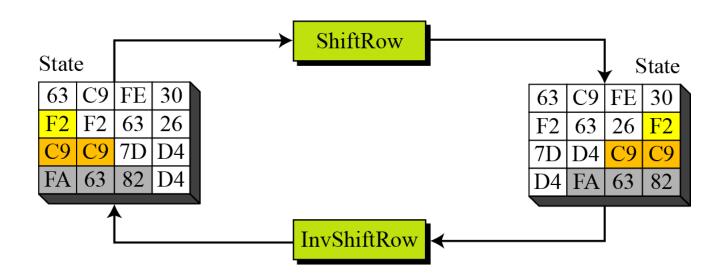
ShiftRows transformation



Example 4

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

ShiftRows transformation in Example 4



Mixing

We need an interbyte transformation that **changes the bits inside a byte**, based on the bits inside the neighboring bytes. We need to mix bytes to **provide diffusion at the bit level**.

Mixing bytes using matrix multiplication

$$a\mathbf{x} + b\mathbf{y} + c\mathbf{z} + d\mathbf{t}$$

$$e\mathbf{x} + f\mathbf{y} + g\mathbf{z} + h\mathbf{t}$$

$$i\mathbf{x} + j\mathbf{y} + k\mathbf{z} + l\mathbf{t}$$

$$m\mathbf{x} + n\mathbf{y} + o\mathbf{z} + p\mathbf{t}$$

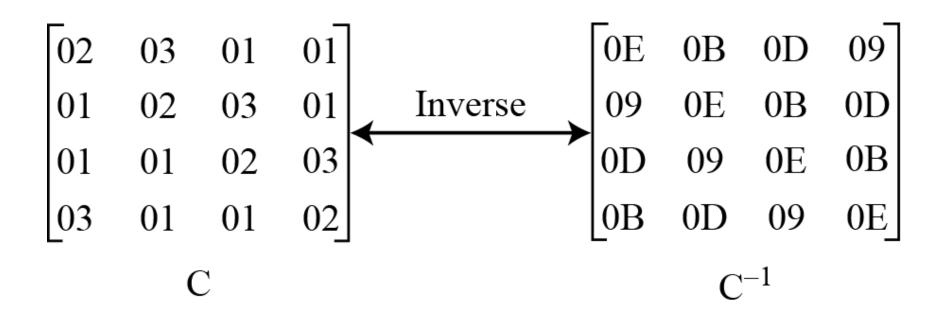
$$= \begin{bmatrix} a & b & c & d \\ e & f & g & h \\ i & j & k & l \\ m & n & o & p \end{bmatrix} \times \begin{bmatrix} \mathbf{x} \\ \mathbf{y} \\ \mathbf{z} \\ \mathbf{t} \end{bmatrix}$$

New matrix

Constant matrix

Old matrix

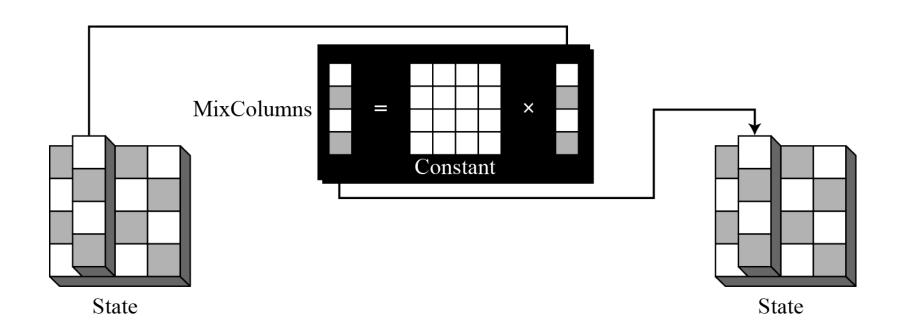
Constant matrices used by MixColumns and InvMixColumns



MixColumns

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

MixColumns transformation



InvMixColumns

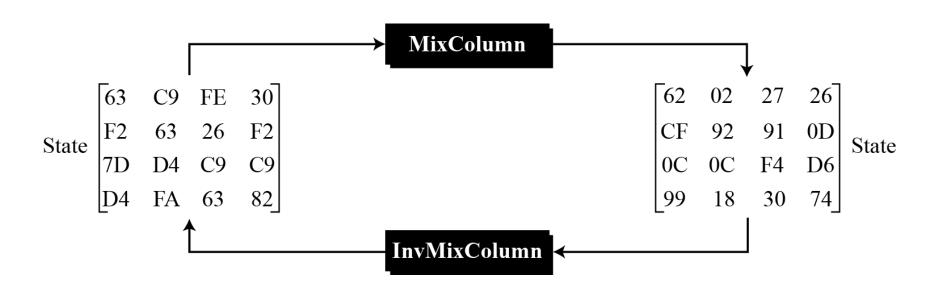
The InvMixColumns transformation is basically the same as the MixColumns transformation.

The MixColumns and InvMixColumns transformations are inverses of each other.

Example 5

Figure shows how a state is transformed using the MixColumns transformation. The figure also shows that the InvMixColumns transformation creates the original one.

The MixColumns transformation in Example 5



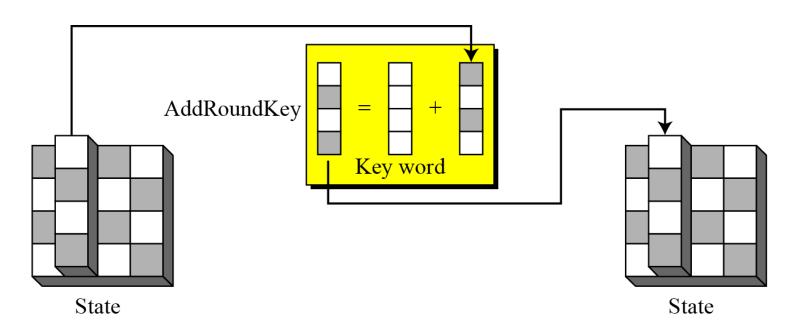
Key Adding

AddRoundKey

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.

The AddRoundKey transformation is the inverse of itself.

AddRoundKey transformation



KEY EXPANSION

To create round keys for each round, AES uses a key-expansion process. If the number of rounds is $N_{\rm r}$, the key-expansion routine creates $N_{\rm r}+1$ 128-bit round keys from one single 128-bit cipher key.

 Table 7.3
 Words for each round

Round		,	Words	
Pre-round	\mathbf{w}_0	\mathbf{w}_1	\mathbf{w}_2	\mathbf{w}_3
1	\mathbf{w}_4	\mathbf{w}_5	\mathbf{w}_6	\mathbf{w}_7
2	\mathbf{w}_8	\mathbf{w}_9	\mathbf{w}_{10}	\mathbf{w}_{11}
N_r	\mathbf{w}_{4N_r}	\mathbf{w}_{4N_r+1}	\mathbf{w}_{4N_r+2}	\mathbf{w}_{4N_r+3}

Key Expansion in AES-128

Key expansion in AES

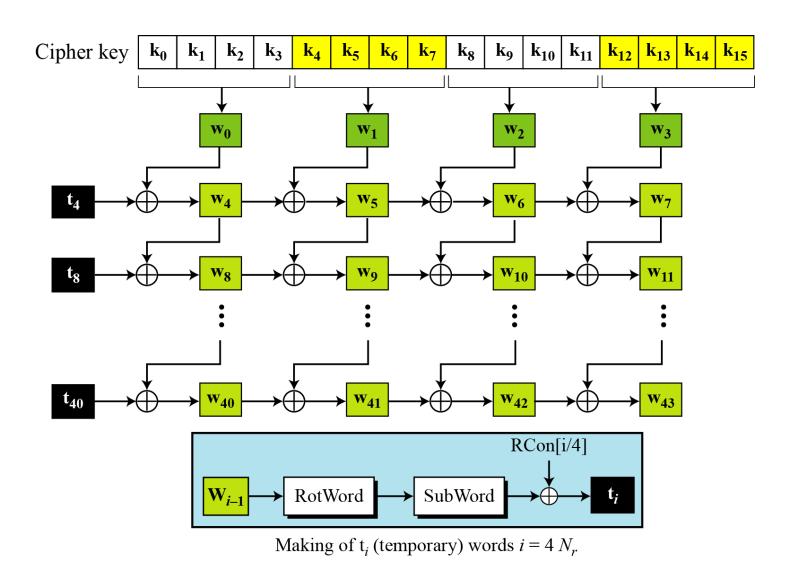


 Table 7.4
 RCon constants

Round	Constant (RCon)	Round	Constant (RCon)
1	(01 00 00 00) ₁₆	6	(<u>20</u> 00 00 00) ₁₆
2	(<u>02</u> 00 00 00) ₁₆	7	(<u>40</u> 00 00 00) ₁₆
3	(<u>04</u> 00 00 00) ₁₆	8	(<u>80</u> 00 00 00) ₁₆
4	(<u>08</u> 00 00 00) ₁₆	9	(<u>1B</u> 00 00 00) ₁₆
5	(<u>10</u> 00 00 00) ₁₆	10	(<u>36</u> 00 00 00) ₁₆

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

 $m(x) = x^8 + x^4 + x^3 + x + 1$

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
_		$w_{00} = 2475 \text{A}2 \text{B}3$	w_{01} = 34755688	$w_{02} = 31E21200$	$w_{03} = 13AA5487$
1	AD20177D	w_{04} = 8955B5CE	$w_{05} = BD20E346$	$w_{06} = 8CC2F146$	$w_{07} = 9$ F68A5C1
2	470678DB	$w_{08} = \text{CE53CD15}$	$w_{09} = 73732E53$	$w_{10} = FFB1DF15$	$w_{11} = 60D97AD4$
3	31DA48D0	$w_{12} = FF8985C5$	$w_{13} = 8$ CFAAB96	$w_{14} = 734B7483$	$w_{15} = 2475$ A2B3
4	47AB5B7D	w_{16} = B822deb8	$w_{17} = 34D8752E$	$w_{18} = 479301$ AD	$w_{19} = 54010$ FFA
5	6C762D20	$w_{20} = D454F398$	$w_{21} = E08C86B6$	$w_{22} = A71F871B$	$w_{23} = F31E88E1$
6	52C4F80D	$w_{24} = 86900B95$	$w_{25} = 661 \text{C8D23}$	$w_{26} = C1030A38$	$w_{27} = 321 D82 D9$
7	E4133523	$w_{28} = 62833 \text{EB}6$	$w_{29} = 049$ FB395	$w_{30} = C59CB9AD$	$w_{31} = F7813B74$
8	8CE29268	$w_{32} = \text{EE61ACDE}$	$w_{33} = EAFE1F4B$	$w_{34} = 2$ F62A6E6	$w_{35} = D8E39D92$
9	0A5E4F61	$w_{36} = E43FE3BF$	$w_{37} = 0$ EC1FCF4	$w_{38} = 21A35A12$	$w_{39} = F940C780$
10	3FC6CD99	$w_{40} = DBF92E26$	$w_{41} = D538D2D2$	$w_{42} = F49B88C0$	$w_{43} = 0$ DDB4F40

Each round key in AES depends on the previous round key. The dependency, however, is **nonlinear** because of SubWord transformation. The addition of the round constants also guarantees that each round key will be different from the previous one.

The two sets of round keys can be created from two cipher keys that are different only in one bit.

Cipher Key 1: 12 45 A2 A1 23 31 A4 A3 B2 CC AA 34 C2 BB 77 23

Cipher Key 2: 12 45 A2 A1 23 31 A4 A3 B2 CC AB 34 C2 BB 77 23

Table 7.6 Comparing two sets of round keys

R.	Round keys for set 1			Round keys for set 2				B. D.	
	1245A2A1	2331A4A3	B2CCA <u>A</u> 34	C2BB7723	1245A2A1	2331A4A3	B2CCA <u>B</u> 34	C2BB7723	01
1	F9B08484	DA812027	684D8 <u>A</u> 13	AAF6F <u>D</u> 30	F9B08484	DA812027	684D8 <u>B</u> 13	AAF6F <u>C</u> 30	02
2	B9E48028	6365A00F	0B282A1C	A1DED72C	В9008028	6381A00F	0BCC2B1C	A13AD72C	17
3	A0EAF11A	C38F5115	C8A77B09	6979AC25	3D0EF11A	5E8F5115	55437A09	F479AD25	30
4	1E7BCEE3	DDF49FF6	1553E4FF	7C2A48DA	839BCEA5	DD149FB0	8857E5B9	7C2E489C	31
5	EB2999F3	36DD0605	238EE2FA	5FA4AA20	A2C910B5	7FDD8F05	F78A6ABC	8BA42220	34
6	82852E3C	B4582839	97D6CAC3	C87260E3	CB5AA788	B487288D	430D4231	C8A96011	56
7	82553FD4	360D17ED	A1DBDD2E	69A9BDCD	588A2560	EC0D0DED	AF004FDC	67A92FCD	50
8	D12F822D	E72295C0	46F948EE	2F50F523	0B9F98E5	E7929508	4892DAD4	2F3BF519	44
9	99C9A438	7EEB31F8	38127916	17428C35	F2794CF0	15EBD9F8	5D79032C	7242F635	51
10	83AD32C8	FD460330	C5547A26	D216F613	E83BDAB0	FDD00348	A0A90064	D2EBF651	52

The concept of weak keys, as we discussed for DES, does not apply to AES. Assume that all bits in the cipher key are 0s. The following shows the words for some rounds:

Pre-round:	0000000	0000000	0000000	00000000
Round 01:	62636363	62636363	62636363	62636363
Round 02:	9B9898C9	F9FBFBAA	9B9898C9	F9FBFBAA
Round 03:	90973450	696CCFFA	F2F45733	0B0FAC99
Round 10:	B4EF5BCB	3E92E211	23E951CF	6F8F188E

The words in the pre-round and the first round are all the same. In the second round, the first word matches with the third; the second word matches with the fourth. However, **after the second round the pattern disappears; every word is different.**

Key Expansion in 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.

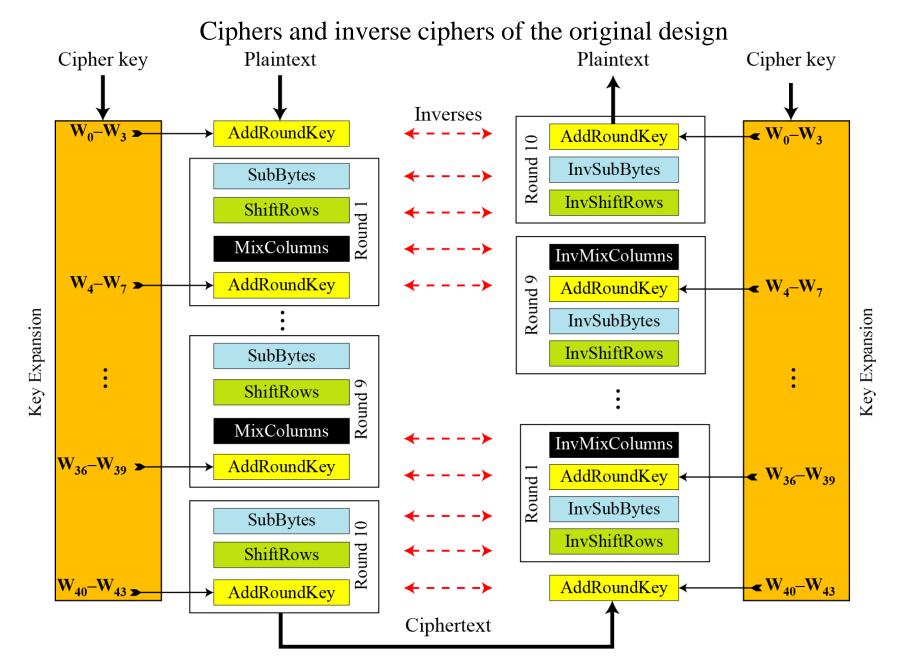
Key-Expansion Analysis

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

CIPHERS

AES uses four types of transformations for encryption and decryption. In the standard, the encryption algorithm is referred to as the cipher and the decryption algorithm as the inverse cipher.

Original Design



Security

AES was designed after DES. Most of the known attacks on DES were already tested on AES.

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.

But side-channel (timing attacks), meet-in-the-middle and Square matrix attacks are under research.

Security

AES structure has advantages and disadvantages.

- Each step consists of a number of operations that can be performed in parallel.
 - •This makes high-speed implementations easy.
 - •But, the decryption operation is significantly different from encryption; we need the inverse lookup table of the S-Box, and the inverse mixing operation is different from the original mixing operation.
- •S-Boxes provide non-linearity and byte shuffle and mixing function provide diffusion.
- •AES designers showed an attack on 6 rounds. Therefore round counts chosen 10-14.
- •In 2009; "Key Recovery Attacks on AES up to 10 rounds" http://eprint.iacr.org/2009/374
- •In 2009; "Related key attacks, Full AES-192 and AES-256" http://eprint.iacr.org/2009/317



All known attacks are theoretical, not practical. AES is already a standard and is using in many real applications.

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.

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.