Advanced Encryption Standard

CSS 322 – Security and Cryptography

Contents

- History of AES
- Simplified AES as an example
- Features of AES

History of AES

- 1977 DES (56-bit key). NIST published.
- 1999 3DES (168-bit key). NIST recommended 3DES be used (DES only for legacy systems)
 - 3DES is considered very secure (no known attacks apart from brute force)
 - But 3DES is very slow, especially in software
 - DES and 3DES use 64-bit blocks larger block sizes required for efficiency
- 1991 IDEA, similar to DES, secure but patent issues
- 1997 NIST called for proposals for new Advanced Encryption Standards
 - Proposals made public and evaluations performed
- 2001 Selected algorithm for AES, Rijndael, published as standard

Selecting a Winner

- Original NIST criteria:
 - Security: effort to cryptoanalyze algorithm, randomness, ...
 - Cost: royalty-free license, computationally efficient, ...
 - Algorithm and implementation characteristics: flexibility (different keys/blocks, implement on different systems), simplicity, ...
- 21 candidate algorithms reduced to 5
- Updated NIST evaluation criteria for 5 algorithms:
 - General Security
 - Software and hardware implementations (needs to be efficient)
 - Low RAM/ROM requirements (e.g. for smart cards)
 - Ability to change keys quickly
 - Potential to use parallel processors

Selecting Rijndael for AES

- Security: good, no known attacks
- Software implementation: fast, can make use of parallel processors
- Hardware implementation: fastest of all candidates
- Low memory requirements: good, except encryption and decryption require separate space
- Timing and Power analysis attacks: easiest to defend against
- Key flexibility: supports on-the-fly change of keys and different size of keys/blocks

Overview of Rijndael/AES

- Rijndael allows variety of block and key sizes
 - 128, 160, 192, 224 and 256 bits
 - Key can be different size to block
- AES standardises block size of 128 bits, key sizes of 128, 192 and 256 bits
- We will use Simplified AES (S-AES) to help understand
 - Again, S-AES is not used in the real world, only an educational tool
- For details of AES (S-Boxes and other operations), see the textbook

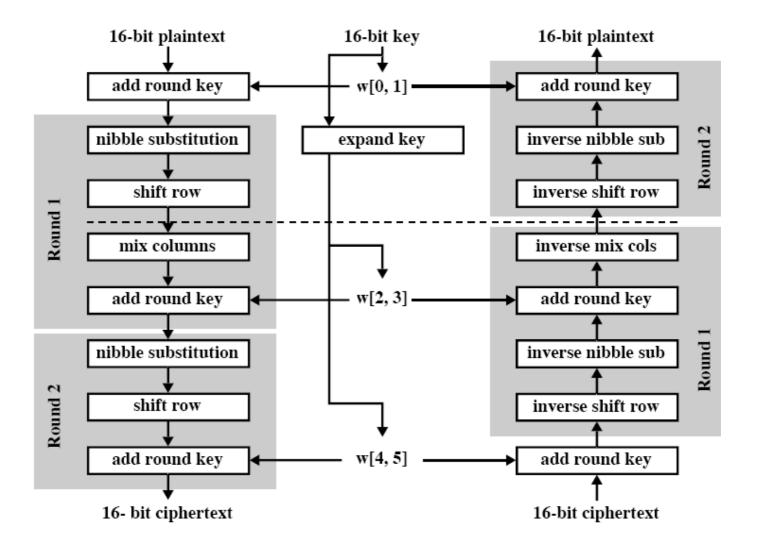
Simplified AES

- Input: 16-bit block of plaintext; 16-bit key
- Output: 16-bit block of ciphertext
- Four operations:
 - 1. Add Key: XOR of a 16-bit key and 16-bit state matrix
 - 2. Nibble substitution: table lookup that swaps nibbles (4-bits)
 - 3. Shift Row: shift of nibbles in a row
 - 4. Mix Column: re-order columns
- 3 rounds:
 - Round 0: Add key
 - Round 1: All four operations
 - Round 2: Three operations

S-AES Encryption and Decryption

ENCRYPTION

DECRYPTION



S-AES State Operations

- S-AES performs operations on 16-bit state matrix
 - View as 4 nibbles (a nibble is 4 bits)
 - Initial value is the 16-bit plaintext

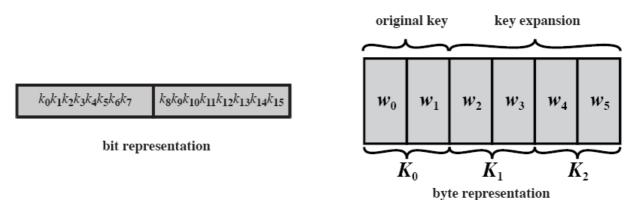
$b_0b_1b_2b_3$	$b_8 b_9 b_{10} b_{11}$
$b_4 b_5 b_6 b_7$	b ₁₂ b ₁₃ b ₁₄ b ₁₅

$S_{0,0}$	$S_{0,1}$
S _{1,0}	<i>S</i> _{1,1}

bit representation

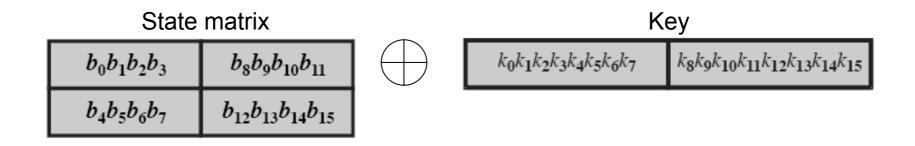
nibble representation

- The original 16-bit key is expanded to 3 x 16-bit round keys

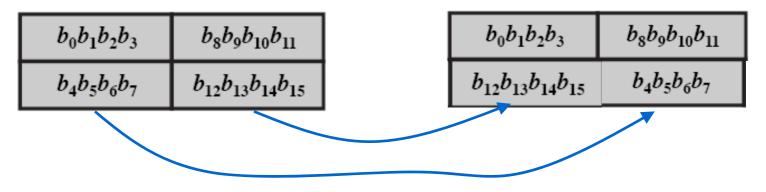


S-AES Add Key and Shift Row

• Add Key: 16-bit State matrix XOR 16-bit key



• Shift Row: swap nibbles on second row of state matrix



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S-AES Nibble Substitution

- Nibble substitution replaces one nibble in state matrix with a new nibble:
 - Substitution is defined by an S-Box
 - Left most 2 bits in state matrix nibble point to row of S-Box
 - Right most 2 bit in state matrix nibble point to column of S-Box
 - State matrix nibble is replaced with S-Box nibble in row/column

	00	01	10	11
00	1001	0100	1010	1011
01	1101	0001	1000 0000	0101
10	0110	0010	0000	0011
11	1100	1110	1111	0111

S-Box (encryption)

	00		10	
00	1010	0101	1001	1011
01	0001	0111	1000	1111
10	0110	0000 0100	0010	0011
11	1100	0100	1101	1110

Inverse S-Box (decryption)

S-AES Mix Column Operation

• Mix the columns in state matrix as follows:

$$\begin{bmatrix} 1 & 4 \\ 4 & 1 \end{bmatrix} \begin{bmatrix} S_{0,0} & S_{0,1} \\ S_{1,0} & S_{1,1} \end{bmatrix} = \begin{bmatrix} S'_{0,0} & S'_{0,1} \\ S'_{1,0} & S'_{1,1} \end{bmatrix}$$
such that:
$$S'_{1,0} = (4 \cdot S_{0,0}) \oplus S_{1,0}$$
$$S'_{0,1} = S_{0,1} \oplus (4 \cdot S_{1,1})$$
$$S'_{1,1} = (4 \cdot S_{0,1}) \oplus S_{1,1}$$

- NOTE: addition and multiplication are performed using GF(2⁴) arithmetic
 - We do not cover fields and Galois fields (GF). Addition and multiplication tables for GF(2⁴) are given in following slides. Details can be found in textbook
- Inverse mix column (for decryption)

$$\begin{bmatrix} 9 & 2 \\ 2 & 9 \end{bmatrix} \begin{bmatrix} S_{0,0} & S_{0,1} \\ S_{1,0} & S_{1,1} \end{bmatrix} = \begin{bmatrix} S'_{0,0} & S'_{0,1} \\ S'_{1,0} & S'_{1,1} \end{bmatrix}$$

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+	0	1	2	3	4	5	6	7	8	9	Α	В	С	D	Е	F
0	0	1	2	3	4	5	6	7	8	9	Α	В	С	D	Е	F
1	1	0	3	2	5	4	7	6	9	8	В	А	D	С	F	Е
2	2	3	0	1	6	7	4	5	Α	В	8	9	Е	F	С	D
3	3	2	1	0	7	6	5	4	В	Α	9	8	F	Е	D	С
4	4	5	6	7	0	1	2	3	С	D	Е	F	8	9	А	В
5	5	4	7	6	1	0	3	2	D	С	F	Е	9	8	В	Α
6	6	7	4	5	2	3	0	1	Е	F	С	D	Α	В	8	9
7	7	6	5	4	3	2	1	0	F	Е	D	С	В	А	9	8
8	8	9	Α	В	С	D	Е	F	0	1	2	3	4	5	6	7
9	9	8	В	А	D	С	F	Е	1	0	3	2	5	4	7	6
Α	Α	В	8	9	Е	F	С	D	2	3	0	1	6	7	4	5
В	В	А	9	8	F	Е	D	С	3	2	1	0	7	6	5	4
С	С	D	Е	F	8	9	Α	В	4	5	6	7	0	1	2	3
D	D	С	F	Е	9	8	В	Α	5	4	7	6	1	0	3	2
Е	Е	F	С	D	А	В	8	9	6	7	4	5	2	3	0	1
F	F	Е	D	С	В	Α	9	8	7	6	5	4	3	2	1	0

Examples: 5+A=F; C+D=1, 1+1=0

GF(2⁴) Multiplication

	0	1	2	3	4	5	6	7	8	9	Α	В	С	D	Е	F
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	1	2	3	4	5	6	7	8	9	А	В	С	D	Е	F
2	0	2	4	6	8	Α	С	Е	3	1	7	5	В	9	F	D
3	0	3	6	5	С	F	Α	9	В	8	D	Е	7	4	1	2
4	0	4	8	С	3	7	В	F	6	2	Е	Α	5	1	D	9
5	0	5	Α	F	7	2	D	8	Е	В	4	1	9	С	3	6
6	0	6	С	Α	В	D	7	1	5	3	9	F	Е	8	2	4
7	0	7	Е	9	F	8	1	6	D	Α	3	4	2	5	С	В
8	0	8	3	В	6	Е	5	D	С	4	F	7	Α	2	9	1
9	0	9	1	8	2	В	3	Α	4	D	5	С	6	F	7	Е
А	0	А	7	D	Е	4	9	3	F	5	8	2	1	В	6	С
В	0	В	5	Е	А	1	F	4	7	С	2	9	D	6	8	3
С	0	С	В	7	5	9	Е	2	Α	6	1	D	F	3	4	8
D	0	D	9	4	1	С	8	5	2	F	В	6	3	Е	А	7
E	0	Е	F	1	D	3	2	С	9	7	6	8	4	Α	В	5
F	0	F	D	2	9	6	4	В	1	Е	С	3	8	7	5	Α

Examples: 5xA=4, CxD=3, 1x1=1

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S-AES Key Expansion

- Original 16-bit key is expanded to 3 x 16-bit keys
 - Represent 16-bit key as two 8-bit word:
 - Key 1: w0, w1
 - Key 2: w2, w3
 - Key 3: w4, w5

 $w_{2} = w_{0} \oplus 1000000 \oplus SubNib(RotNib(w_{1}))$ $w_{3} = w_{2} \oplus w_{1}$ $w_{4} = w_{2} \oplus 00110000 \oplus SubNib(RotNib(w_{3}))$ $w_{5} = w_{4} \oplus w_{3}$

 where RotNib swaps the left nibble with the right nibble and SubNib is a substitution as defined on previous slide

Comparing S-AES and AES

- S-AES
 - 16-bit key
 - 16-bit plaintext/ciphertext
 - 2 rounds
 - First with all four operations
 - Last with 3 operations
 - Round key size: 16 bits
 - Mix Columns: arithmetic over GF(2⁴)

- AES-128
 - 128-bit key
 - 128 bit plaintext/ciphertext
 - 10 rounds
 - 9 with all four operations
 - Last with 3 operations
 - Round key size: 128 bits
 - Mix Columns: arithmetic over GF(2⁸)

Principles of operation are the same Details of AES can be found in textbook and standard

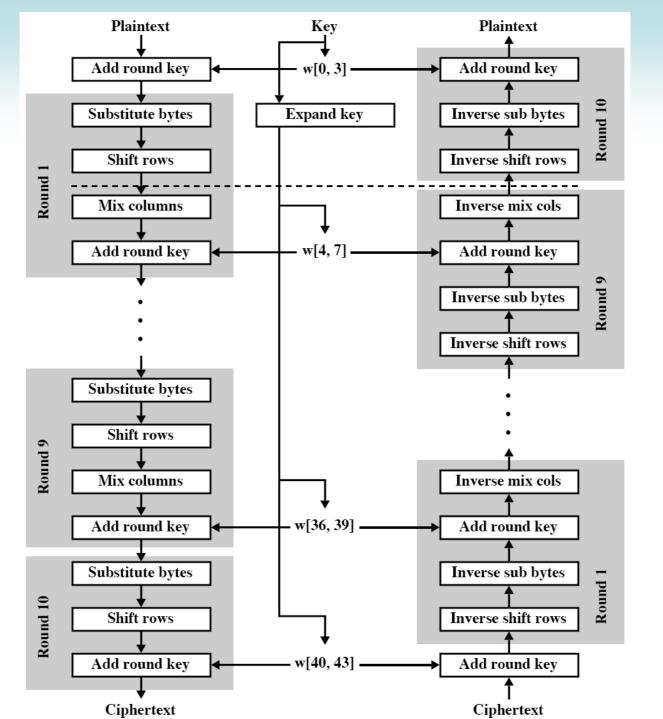
AES Design Features

- Only the Add Key stage makes use of the key
 - The other 3 stages (Shift Row, Mix Column, Nibble Substitution) provide confusion and diffusion of bits. On their own, they provide no security (do not use key)
- The four operations are easily reversible (for decryption)
- Encryption and decryption algorithms not identical
- Final round is only 3 operations, so algorithm is reversible
- S-Box design aims:
 - Low correlation between input bits and output bits
 - Cannot describe output as simple function of input
 - No fixed or opposite points, for example S-box(a) \neq a
- Mix columns and shift rows ensure all output bits depend on all input bits after several rounds
- In Mix Columns, encryption more efficient than decryption
 - Only encryption used CFB/OFB modes for block ciphers and for message authentication
- Very efficient implementations for 8- and 32-bit processors

AES Parameters

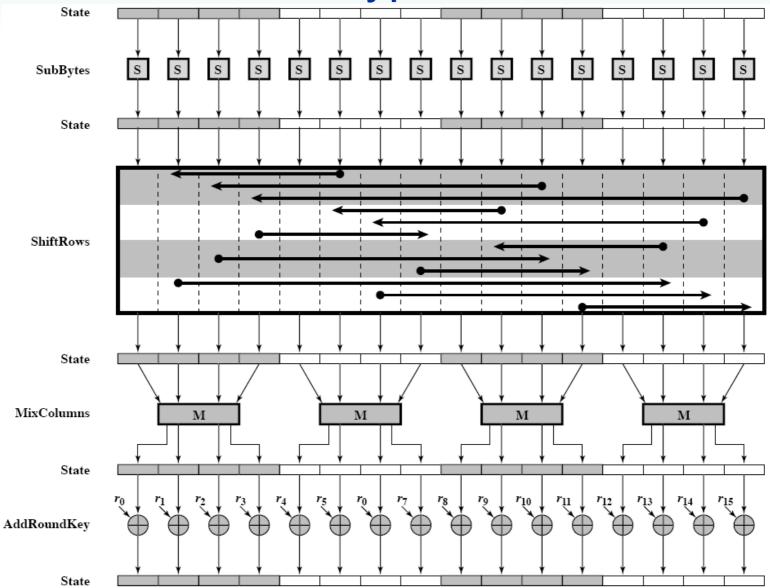
Key size (words/bytes/bits)	4/16/128	6/24/192	8/32/256
Plaintext block size (words/bytes/bits)	4/16/128	4/16/128	4/16/128
Number of rounds	10	12	14
Round key size (words/bytes/bits)	4/16/128	4/16/128	4/16/128
Expanded key size (words/bytes)	44/176	52/208	60/240

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AES Encryption Round



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