Advanced Encryption Standard

Cryptography

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aes.tex, r1980

Contents

History of AES

- 1977: DES (56-bit key). NIST published.
- 1991: IDEA, similar to DES, secure but patent issues
- 1999: 3DES (168-bit key). NIST recommended 3DES be used (DES only for legacy systems)
  - 3DES was considered secure (apart from special case attacks)
  - But 3DES is very slow, especially in software
  - DES and 3DES use 64-bit blocks – larger block sizes required for efficiency
- 1997: NIST called for proposals for new Advanced Encryption Standards
  - Proposals made public and evaluations performed
- 2001: Selected *Rijndael* as the algorithm for AES

Selecting a Winner

- Original NIST criteria:
  - Security: effort to cryptoanalyse 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 AES

- NIST Advanced Encryption Standard, FIPS-197, 2001
- Three variations of same algorithm standardised
  - AES-128: 128-bit key, 10 rounds
  - AES-192: 192-bit key, 12 rounds
  - AES-256: 256-bit key, 14 rounds
- AES uses 128-bit block size for all variations
- S-AES used to understand AES (educational only)
- For details of AES see the Stallings textbook, AES on Wikipedia or the AES standard from NIST

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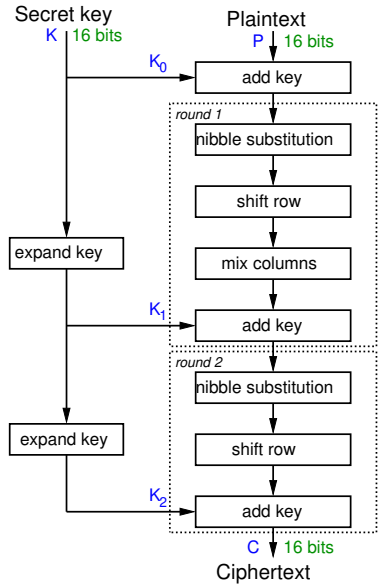
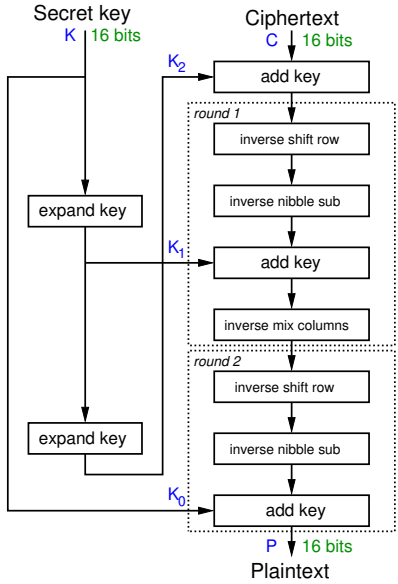
Simplified-AES

- Educational purposes only. Mohammad A. Musa , Edward F. Schaefer and Stephen Wedig (2003) A Simplified AES Algorithm and its Linear and Differential Cryptanalyses, Cryptologia, 27:2, 148-177, DOI: 10.1080/0161-110391891838
- Input: 16-bit block of plaintext; 16-bit key
- Output: 16-bit block of ciphertext
- Operations:
  - Add Key: XOR of a 16-bit key and 16-bit state matrix
  - Nibble Substitution: S-Box table lookup that swaps nibbles (4 bits)
  - Shift Row: shift of nibbles in a row
  - Mix Column: re-order columns
  - Rotate Nibbles: swap the nibbles
- 3 rounds (although they don't contain same operations)

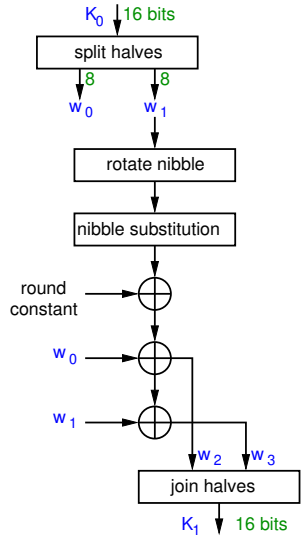
S-AES Encryption



S-AES Decryption



S-AES Key Generation for Round 1



S-AES State Matrix (definition)

S-AES operates on a 16-bit state matrix, viewed as 4 nibbles

$$\begin{bmatrix} b_0 b_1 b_2 b_3 & b_8 b_9 b_{10} b_{11} \\ b_4 b_5 b_6 b_7 & b_{12} b_{13} b_{14} b_{15} \end{bmatrix} = \begin{bmatrix} S_{0,0} & S_{0,1} \\ S_{1,0} & S_{1,1} \end{bmatrix}$$

S-AES Shift Row, Add Key and Rotate Nibbile operations (definition)

S-AES Shift Row:

$$\begin{bmatrix} S_{0,0} & S_{0,1} \\ S_{1,0} & S_{1,1} \end{bmatrix} \rightarrow \begin{bmatrix} S_{0,0} & S_{0,1} \\ S_{1,1} & S_{1,0} \end{bmatrix}$$

S-AES Add Key: Exclusive OR (XOR)

S-AES Rotate Nibble: swap the two nibbles

S-AES Nibble Substitution: apply S-Box on each nibble

S-AES Round Constant 1: 10000000

S-AES Round Constant 2: 00110000

S-AES S-Boxes (definition)

S-Box considered as a matrix: input used to select row/column; selected element is output

Input: 4-bit nibble, $bit_1, bit_2, bit_3, bit_4$

$bit_1 bit_2$ specifies row

$bit_3 bit_4$ specifies column

$$\text{encrypt}: \begin{bmatrix} 1001 & 0100 & 1010 & 1011 \\ 1101 & 0001 & 1000 & 0101 \\ 0110 & 0010 & 0000 & 0011 \\ 1100 & 1110 & 1111 & 0111 \end{bmatrix}$$

$$\text{decrypt}: \begin{bmatrix} 1010 & 0101 & 1001 & 1011 \\ 0001 & 0111 & 1000 & 1111 \\ 0110 & 0000 & 0010 & 0011 \\ 1100 & 0100 & 1101 & 1110 \end{bmatrix}$$

S-AES Mix Columns (definition)

Mix the columns in the state matrix be performing a matrix multiplication.

Mix Columns:

$$\begin{bmatrix} S'_{0,0} & S'_{0,1} \\ S'_{1,0} & S'_{1,1} \end{bmatrix} = \begin{bmatrix} 1 & 4 \\ 4 & 1 \end{bmatrix} \begin{bmatrix} S_{0,0} & S_{0,1} \\ S_{1,0} & S_{1,1} \end{bmatrix}$$

Inverse Mix Columns:

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

Galois Field GF(2^4) is used for addition and multiplication operations.

S-AES Mix Columns (Simple) (definition)

Mix the columns in the state matrix be performing the following calculations.

Mix Columns:

$$S'_{0,0} = S_{0,0} \oplus (0100 \times S_{1,0})$$
$$S'_{1,0} = (0100 \times S_{0,0}) \oplus S_{1,0}$$
$$S'_{0,1} = S_{0,1} \oplus (0100 \times S_{1,1})$$
$$S'_{1,1} = (0100 \times S_{0,1}) \oplus S_{1,1}$$

Inverse Mix Columns:

$$S'_{0,0} = (1001 \times S_{0,0}) \oplus (0010 \times S_{1,0})$$
$$S'_{1,0} = (0010 \times S_{0,0}) \oplus (1001 \times S_{1,0})$$
$$S'_{0,1} = (1001 \times S_{0,1}) \oplus (0010 \times S_{1,1})$$
$$S'_{1,1} = (0010 \times S_{0,1}) \oplus (1001 \times S_{1,1})$$

For multiplication, lookup using The figure on slide 17.

GF(2^4) Multiplication Table used in S-AES

x	0000	0001	0010	0011	0100	0101	0110	0111	1000	1001	1010	1011	1100	1101	1110	1111
0000	0000	0000	0000	0000	0000	0000	0000	0000	0000	0000	0000	0000	0000	0000	0000	0000
0001	0000	0001	0010	0011	0100	0101	0110	0111	1000	1001	1010	1011	1100	1101	1110	1111
0010	0000	0010	0100	0110	1000	1010	1100	1110	0011	0001	0111	0101	1011	1001	1111	1101
0011	0000	0011	0110	0101	1100	1111	1010	1001	1011	1000	1101	1110	0111	0100	0001	0010
0100	0000	0100	1000	1100	0011	0111	1011	1111	0110	0010	1110	1010	0101	0001	1101	1001
0101	0000	0101	1010	1111	0111	0010	1101	1000	1110	1011	0100	0001	1001	1100	0011	0110
0110	0000	0110	1100	1010	1011	1101	0111	0001	0101	0011	1001	1111	1110	1000	0010	0100
0111	0000	0111	1110	1001	1111	1000	0001	0110	1101	1010	0011	0100	0010	0101	1100	1011
1000	0000	1000	0011	1011	0110	1110	0101	1101	1100	0100	1111	0111	1010	0010	1001	0001
1001	0000	1001	0001	1000	0010	1011	0011	1010	0100	1101	0101	1100	0110	1111	0111	1110
1010	0000	1010	0111	1101	1110	0100	1001	0011	1111	0101	1000	0010	0001	1011	0110	1100
1011	0000	1011	0101	1110	1010	0001	1111	0100	0111	1100	0010	1001	1101	0110	1000	0011
1100	0000	1100	1011	0111	0101	1001	1110	0010	1010	0110	0001	1101	1111	0011	0100	1000
1101	0000	1101	1001	0100	0001	1100	1000	0101	0010	1111	1011	0110	0011	1110	1010	0111
1110	0000	1110	1111	0001	1101	0011	0010	1100	1001	0111	0110	1000	0100	1010	1011	0101
1111	0000	1111	1101	0010	1001	0110	0100	1011	0001	1110	1100	0011	1000	0111	0101	1010

Comparing S-AES and AES-128

- S-AES
  - 16-bit key, 16-bit plaintext/ciphertext
  - 2 rounds: first with all 4 operations, last with 3 operations
  - Round key size: 16 bits
  - Mix Columns: arithmetic over GF(2^4)
- AES-128
  - 128-bit key, 128-bit plaintext/ciphertext
  - 10 rounds: first 9 with all 4 operations, last with 3 operations
  - Round key size: 128 bits
  - Mix Columns: arithmetic over GF(2^8)
- Principles of operation are the same

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Encrypt with S-AES (exercise)

Show that when the plaintext 1101 0111 0010 1000 is encrypted using Simplified-AES with key 0100 1010 1111 0101 that the ciphertext obtained is 0010 0100 1110 1100.

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AES Key Generation (exercise)

Generate a shared secret key to be used with AES and share it with another person.

AES Encryption (exercise)

Create a message in a plain text file and after using AES, send the ciphertext to the person you shared the key with.

AES Decryption (exercise)

Decrypt the ciphertext you received.

AES Performance Benchmarking (exercise)

Perform speed tests on AES using both the software and hardware implementations (if available). Compare and discuss the impact of the following on performance: key length; software vs hardware; different computers (e.g. compare the performance with another person).

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AES in Python Cryptography Library

- `https://cryptography.io/en/latest/hazmat/primitives/symmetric-encryption/`