Federal Information
Processing Standards Publication 197

November 26, 2001

Announcing the

ADVANCED ENCRYPTION STANDARD (AES)

Federal Information Processing Standards Publications (FIPS PUBS) are issued by the National Institute of Standards and Technology (NIST) after approval by the Secretary of Commerce pursuant to Section 5131 of the Information Technology Management Reform Act of 1996 (Public Law 104-106) and the Computer Security Act of 1987 (Public Law 100-235).

3. Explanation. The Advanced Encryption Standard (AES) specifies a FIPS-approved cryptographic algorithm that can be used to protect electronic data. The AES algorithm is a symmetric block cipher that can encrypt (encipher) and decrypt (decipher) information. Encryption converts data to an unintelligible form called ciphertext; decrypting the ciphertext converts the data back into its original form, called plaintext.

The AES algorithm is capable of using cryptographic keys of 128, 192, and 256 bits to encrypt and decrypt data in blocks of 128 bits.
4. Approving Authority. Secretary of Commerce.
6. Applicability. This standard may be used by Federal departments and agencies when an agency determines that sensitive (unclassified) information (as defined in P. L. 100-235) requires cryptographic protection.

Other FIPS-approved cryptographic algorithms may be used in addition to, or in lieu of, this standard. Federal agencies or departments that use cryptographic devices for protecting classified information can use those devices for protecting sensitive (unclassified) information in lieu of this standard.

In addition, this standard may be adopted and used by non-Federal Government organizations. Such use is encouraged when it provides the desired security for commercial and private organizations.

8. **Implementations.** The algorithm specified in this standard may be implemented in software, firmware, hardware, or any combination thereof. The specific implementation may depend on several factors such as the application, the environment, the technology used, etc. The algorithm shall be used in conjunction with a FIPS approved or NIST recommended mode of operation. Object Identifiers (OIDs) and any associated parameters for AES used in these modes are available at the Computer Security Objects Register (CSOR), located at [http://csrc.nist.gov/csor](http://csrc.nist.gov/csor) [2].

Implementations of the algorithm that are tested by an accredited laboratory and validated will be considered as complying with this standard. Since cryptographic security depends on many factors besides the correct implementation of an encryption algorithm, Federal Government employees, and others, should also refer to NIST Special Publication 800-21, *Guideline for Implementing Cryptography in the Federal Government*, for additional information and guidance (NIST SP 800-21 is available at [http://csrc.nist.gov/publications](http://csrc.nist.gov/publications)).

9. **Implementation Schedule.** This standard becomes effective on May 26, 2002.

10. **Patents.** Implementations of the algorithm specified in this standard may be covered by U.S. and foreign patents.

11. **Export Control.** Certain cryptographic devices and technical data regarding them are subject to Federal export controls. Exports of cryptographic modules implementing this standard and technical data regarding them must comply with these Federal regulations and be licensed by the Bureau of Export Administration of the U.S. Department of Commerce. Applicable Federal government export controls are specified in Title 15, Code of Federal Regulations (CFR) Part 740.17; Title 15, CFR Part 742; and Title 15, CFR Part 774, Category 5, Part 2.

12. **Qualifications.** NIST will continue to follow developments in the analysis of the AES algorithm. As with its other cryptographic algorithm standards, NIST will formally reevaluate this standard every five years.

Both this standard and possible threats reducing the security provided through the use of this standard will undergo review by NIST as appropriate, taking into account newly available analysis and technology. In addition, the awareness of any breakthrough in technology or any mathematical weakness of the algorithm will cause NIST to reevaluate this standard and provide necessary revisions.

13. **Waiver Procedure.** Under certain exceptional circumstances, the heads of Federal agencies, or their delegates, may approve waivers to Federal Information Processing Standards (FIPS). The heads of such agencies may redelegate such authority only to a senior official designated pursuant to Section 3506(b) of Title 44, U.S. Code. Waivers shall be granted only when compliance with this standard would

   a. adversely affect the accomplishment of the mission of an operator of Federal computer system or

   b. cause a major adverse financial impact on the operator that is not offset by government-wide savings.
Agency heads may act upon a written waiver request containing the information detailed above. Agency heads may also act without a written waiver request when they determine that conditions for meeting the standard cannot be met. Agency heads may approve waivers only by a written decision that explains the basis on which the agency head made the required finding(s). A copy of each such decision, with procurement sensitive or classified portions clearly identified, shall be sent to: National Institute of Standards and Technology; ATTN: FIPS Waiver Decision, Information Technology Laboratory, 100 Bureau Drive, Stop 8900, Gaithersburg, MD 20899-8900.

In addition, notice of each waiver granted and each delegation of authority to approve waivers shall be sent promptly to the Committee on Government Operations of the House of Representatives and the Committee on Government Affairs of the Senate and shall be published promptly in the Federal Register.

When the determination on a waiver applies to the procurement of equipment and/or services, a notice of the waiver determination must be published in the Commerce Business Daily as a part of the notice of solicitation for offers of an acquisition or, if the waiver determination is made after that notice is published, by amendment to such notice.

A copy of the waiver, any supporting documents, the document approving the waiver and any supporting and accompanying documents, with such deletions as the agency is authorized and decides to make under Section 552(b) of Title 5, U.S. Code, shall be part of the procurement documentation and retained by the agency.

14. Where to obtain copies. This publication is available electronically by accessing [http://csrc.nist.gov/publications/](http://csrc.nist.gov/publications/). A list of other available computer security publications, including ordering information, can be obtained from NIST Publications List 91, which is available at the same web site. Alternatively, copies of NIST computer security publications are available from: National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, VA 22161.
# Federal Information Processing Standards Publication 197

November 26, 2001

## Specification for the Advanced Encryption Standard (AES)

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1. Introduction

This standard specifies the Rijndael algorithm ([3] and [4]), a symmetric block cipher that can process data blocks of 128 bits, using cipher keys with lengths of 128, 192, and 256 bits. Rijndael was designed to handle additional block sizes and key lengths, however they are not adopted in this standard.

Throughout the remainder of this standard, the algorithm specified herein will be referred to as “the AES algorithm.” The algorithm may be used with the three different key lengths indicated above, and therefore these different “flavors” may be referred to as “AES-128”, “AES-192”, and “AES-256”.

This specification includes the following sections:

2. Definitions of terms, acronyms, and algorithm parameters, symbols, and functions;
3. Notation and conventions used in the algorithm specification, including the ordering and numbering of bits, bytes, and words;
4. Mathematical properties that are useful in understanding the algorithm;
5. Algorithm specification, covering the key expansion, encryption, and decryption routines;
6. Implementation issues, such as key length support, keying restrictions, and additional block/key/round sizes.

The standard concludes with several appendices that include step-by-step examples for Key Expansion and the Cipher, example vectors for the Cipher and Inverse Cipher, and a list of references.

2. Definitions

2.1 Glossary of Terms and Acronyms

The following definitions are used throughout this standard:

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
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<tr>
<td>AES</td>
<td>Advanced Encryption Standard</td>
</tr>
<tr>
<td>Affine</td>
<td>A transformation consisting of multiplication by a matrix followed by</td>
</tr>
<tr>
<td>Transformation</td>
<td>the addition of a vector.</td>
</tr>
<tr>
<td>Array</td>
<td>An enumerated collection of identical entities (e.g., an array of bytes).</td>
</tr>
<tr>
<td>Bit</td>
<td>A binary digit having a value of 0 or 1.</td>
</tr>
<tr>
<td>Block</td>
<td>Sequence of binary bits that comprise the input, output, State, and</td>
</tr>
<tr>
<td></td>
<td>Round Key. The length of a sequence is the number of bits it contains.</td>
</tr>
<tr>
<td></td>
<td>Blocks are also interpreted as arrays of bytes.</td>
</tr>
<tr>
<td>Byte</td>
<td>A group of eight bits that is treated either as a single entity or as an</td>
</tr>
<tr>
<td></td>
<td>array of 8 individual bits.</td>
</tr>
</tbody>
</table>
Cipher
Series of transformations that converts plaintext to ciphertext using the Cipher Key.

Cipher Key
Secret, cryptographic key that is used by the Key Expansion routine to generate a set of Round Keys; can be pictured as a rectangular array of bytes, having four rows and $N_k$ columns.

Ciphertext
Data output from the Cipher or input to the Inverse Cipher.

Inverse Cipher
Series of transformations that converts ciphertext to plaintext using the Cipher Key.

Key Expansion
Routine used to generate a series of Round Keys from the Cipher Key.

Plaintext
Data input to the Cipher or output from the Inverse Cipher.

Rijndael
Cryptographic algorithm specified in this Advanced Encryption Standard (AES).

Round Key
Round keys are values derived from the Cipher Key using the Key Expansion routine; they are applied to the State in the Cipher and Inverse Cipher.

State
Intermediate Cipher result that can be pictured as a rectangular array of bytes, having four rows and $N_b$ columns.

S-box
Non-linear substitution table used in several byte substitution transformations and in the Key Expansion routine to perform a one-for-one substitution of a byte value.

Word
A group of 32 bits that is treated either as a single entity or as an array of 4 bytes.

2.2 Algorithm Parameters, Symbols, and Functions
The following algorithm parameters, symbols, and functions are used throughout this standard:

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 $N_b = 4$, the Round Key length equals 128 bits/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().

$K$ 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.

\( Nb \) Number of columns (32-bit words) comprising the State. For this standard, \( Nb = 4 \). (Also see Sec. 6.3.)

\( Nk \) Number of 32-bit words comprising the Cipher Key. For this standard, \( Nk = 4, 6, \) or 8. (Also see Sec. 6.3.)

\( Nr \) Number of rounds, which is a function of \( Nk \) and \( Nb \) (which is fixed). For this standard, \( Nr = 10, 12, \) or 14. (Also see Sec. 6.3.)

Rcon[] The round constant word array.

RotWord() Function used in the Key Expansion routine that takes a four-byte word and performs 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 non-linear byte substitution table (S-box) that operates on each of the State bytes independently.

SubWord() Function used in the Key Expansion routine that takes a four-byte input word and applies an S-box to each of the four bytes to produce an output word.

XOR Exclusive-OR operation.

\( \oplus \) Exclusive-OR operation.

\( \otimes \) Multiplication of two polynomials (each with degree < 4) modulo \( x^4 + 1 \).

\( \cdot \) Finite field multiplication.

3. Notation and Conventions

3.1 Inputs and Outputs

The input and output for the AES algorithm each consist of sequences of 128 bits (digits with values of 0 or 1). These sequences will sometimes be referred to as blocks and the number of bits they contain will be referred to as their length. The Cipher Key for the AES algorithm is a sequence of 128, 192 or 256 bits. Other input, output and Cipher Key lengths are not permitted by this standard.

The bits within such sequences will be numbered starting at zero and ending at one less than the sequence length (block length or key length). The number \( i \) attached to a bit is known as its index and will be in one of the ranges \( 0 \leq i < 128 \), \( 0 \leq i < 192 \) or \( 0 \leq i < 256 \) depending on the block length and key length (specified above).
3.2 Bytes

The basic unit for processing in the AES algorithm is a byte, a sequence of eight bits treated as a single entity. The input, output and Cipher Key bit sequences described in Sec. 3.1 are processed as arrays of bytes that are formed by dividing these sequences into groups of eight contiguous bits to form arrays of bytes (see Sec. 3.3). For an input, output or Cipher Key denoted by \( a \), the bytes in the resulting array will be referenced using one of the two forms, \( a_n \) or \( a[n] \), where \( n \) will be in one of the following ranges:

- Key length = 128 bits, \( 0 \leq n < 16 \);
- Block length = 128 bits, \( 0 \leq n < 16 \);
- Key length = 192 bits, \( 0 \leq n < 24 \);
- Key length = 256 bits, \( 0 \leq n < 32 \).

All byte values in the AES algorithm will be presented as the concatenation of its individual bit values (0 or 1) between braces in the order \{b_7, b_6, b_5, b_4, b_3, b_2, b_1, b_0\}. These bytes are interpreted as finite field elements using a polynomial representation:

\[
b_7x^7 + b_6x^6 + b_5x^5 + b_4x^4 + b_3x^3 + b_2x^2 + b_1x + b_0 = \sum_{i=0}^{7} b_ix^i. \tag{3.1}
\]

For example, \{01100011\} identifies the specific finite field element \( x^6 + x^5 + x + 1 \).

It is also convenient to denote byte values using hexadecimal notation with each of two groups of four bits being denoted by a single character as in Fig. 1.

![Figure 1. Hexadecimal representation of bit patterns.](image)

Hence the element \{01100011\} can be represented as \{63\}, where the character denoting the four-bit group containing the higher numbered bits is again to the left.

Some finite field operations involve one additional bit \( b_8 \) to the left of an 8-bit byte. Where this extra bit is present, it will appear as '01' immediately preceding the 8-bit byte; for example, a 9-bit sequence will be presented as \{01\}{1b}.

3.3 Arrays of Bytes

Arrays of bytes will be represented in the following form:

\[ a_0a_1a_2...a_{15} \]

The bytes and the bit ordering within bytes are derived from the 128-bit input sequence

\[ \text{input}_0 \text{ input}_1 \text{ input}_2 \ldots \text{input}_{126} \text{ input}_{127} \]

as follows:
\( a_0 = \{ \text{input}_0, \text{input}_1, \ldots, \text{input}_7 \}; \)

\( a_1 = \{ \text{input}_8, \text{input}_9, \ldots, \text{input}_{15} \}; \)

\[ \vdots \]

\( a_{15} = \{ \text{input}_{120}, \text{input}_{121}, \ldots, \text{input}_{127} \}. \)

The pattern can be extended to longer sequences (i.e., for 192- and 256-bit keys), so that, in general,

\[ a_n = \{ \text{input}_{8n}, \text{input}_{8n+1}, \ldots, \text{input}_{8n+7} \}. \]

Taking Sections 3.2 and 3.3 together, Fig. 2 shows how bits within each byte are numbered.

<table>
<thead>
<tr>
<th>Input bit sequence</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
<th>18</th>
<th>19</th>
<th>20</th>
<th>21</th>
<th>22</th>
<th>23</th>
<th>…</th>
</tr>
</thead>
<tbody>
<tr>
<td>Byte number</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Bit numbers in byte</td>
<td>7</td>
<td>6</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>7</td>
<td>6</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>7</td>
<td>6</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>7</td>
</tr>
</tbody>
</table>

**Figure 2. Indices for Bytes and Bits.**

### 3.4 The State

Internally, the 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 \( Nb \) bytes, where \( Nb \) is the block length divided by 32. In the State array denoted by the symbol \( s \), each individual byte has two indices, with its row number \( r \) in the range \( 0 \leq r < 4 \) and its column number \( c \) in the range \( 0 \leq c < Nb \). This allows an individual byte of the State to be referred to as either \( s_{r,c} \) or \( s[r,c] \). For this standard, \( Nb=4 \), i.e., \( 0 \leq c < 4 \) (also see Sec. 6.3).

At the start of the Cipher and Inverse Cipher described in Sec. 5, the input – the array of bytes \( in_0, in_1, \ldots, in_{15} \) – is copied into the State array as illustrated in Fig. 3. The Cipher or Inverse Cipher operations are then conducted on this State array, after which its final value is copied to the output – the array of bytes \( out_0, out_1, \ldots, out_{15} \).

![State array input and output](image)

Hence, at the beginning of the Cipher or Inverse Cipher, the input array, \( in \), is copied to the State array according to the scheme:

\[ s[r, c] = in[r + 4c] \quad \text{for } 0 \leq r < 4 \text{ and } 0 \leq c < Nb, \]

(3.3)
and at the end of the Cipher and Inverse Cipher, the State is copied to the output array $out$ as follows:

$$out[r + 4c] = s[r, c] \quad \text{for } 0 \leq r < 4 \text{ and } 0 \leq c < Nb. \quad (3.4)$$

### 3.5 The State as an Array of Columns

The four bytes in each column of the State array form 32-bit words, where the row number $r$ provides an index for the four bytes within each word. The state can hence be interpreted as a one-dimensional array of 32 bit words (columns), $w_0...w_3$, where the column number $c$ provides an index into this array. Hence, for the example in Fig. 3, the State can be considered as an array of four words, as follows:

$$w_0 = s_{0,0} s_{1,0} s_{2,0} s_{3,0} \quad w_1 = s_{0,1} s_{1,1} s_{2,1} s_{3,1}$$

$w_2 = s_{0,2} s_{1,2} s_{2,2} s_{3,2}$

$w_3 = s_{0,3} s_{1,3} s_{2,3} s_{3,3}.$ \quad (3.5)

### 4. Mathematical Preliminaries

All bytes in the AES algorithm are interpreted as finite field elements using the notation introduced in Sec. 3.2. Finite field elements can be added and multiplied, but these operations are different from those used for numbers. The following subsections introduce the basic mathematical concepts needed for Sec. 5.

#### 4.1 Addition

The addition of two elements in a finite field is achieved by “adding” the coefficients for the corresponding powers in the polynomials for the two elements. The addition is performed with the XOR operation (denoted by $\oplus$) - i.e., modulo 2 - so that $1 \oplus 1 = 0$, $1 \oplus 0 = 1$, and $0 \oplus 0 = 0$. Consequently, subtraction of polynomials is identical to addition of polynomials.

Alternatively, addition of finite field elements can be described as the modulo 2 addition of corresponding bits in the byte. For two bytes \{$a_7a_6a_5a_4a_3a_2a_1a_0$\} and \{$b_7b_6b_5b_4b_3b_2b_1b_0$\}, the sum is \{$c_7c_6c_5c_4c_3c_2c_1c_0$\}, where each $c_i = a_i \oplus b_i$ (i.e., $c_7 = a_7 \oplus b_7$, $c_6 = a_6 \oplus b_6$, ... $c_0 = a_0 \oplus b_0$).

For example, the following expressions are equivalent to one another:

$$(x^6 + x^4 + x^2 + x + 1) + (x^7 + x + 1) = x^7 + x^6 + x^4 + x^2 \quad \text{(polynomial notation);}$$

$$\{01010111\} \oplus \{10000011\} = \{11010100\} \quad \text{(binary notation);}$$

$$\{57\} \oplus \{83\} = \{d4\} \quad \text{(hexadecimal notation).}$$

#### 4.2 Multiplication

In the polynomial representation, multiplication in $GF(2^8)$ (denoted by $\cdot$) corresponds with the multiplication of polynomials modulo an irreducible polynomial of degree 8. A polynomial is irreducible if its only divisors are one and itself. For the AES algorithm, this irreducible polynomial is

$$m(x) = x^8 + x^4 + x^3 + x + 1, \quad (4.1)$$

$10$
or \{01\}\{1b\} in hexadecimal notation.

For example, \{57\} \cdot \{83\} = \{c1\}, because
\[
\begin{align*}
(x^6 + x^4 + x^2 + x + 1) & \cdot (x^7 + x + 1) = x^{13} + x^{11} + x^9 + x^8 + x^7 + x^6 + x^4 + x^2 + x + 1 \\
& = x^{13} + x^{11} + x^9 + x^8 + x^6 + x^5 + x^4 + x^3 + 1
\end{align*}
\]
and
\[
\begin{align*}
x^{13} + x^{11} + x^9 + x^8 + x^6 + x^5 + x^4 + x^3 + 1 \mod (x^8 + x^4 + x^3 + x + 1) & = x^7 + x^6 + 1.
\end{align*}
\]

The modular reduction by \(m(x)\) ensures that the result will be a binary polynomial of degree less than 8, and thus can be represented by a byte. Unlike addition, there is no simple operation at the byte level that corresponds to this multiplication.

The multiplication defined above is associative, and the element \{01\} is the multiplicative identity. For any non-zero binary polynomial \(b(x)\) of degree less than 8, the multiplicative inverse of \(b(x)\), denoted \(b^{-1}(x)\), can be found as follows: the extended Euclidean algorithm [7] is used to compute polynomials \(a(x)\) and \(c(x)\) such that
\[
b(x)a(x) + m(x)c(x) = 1.
\]
Hence, \(a(x) \cdot b(x) \mod m(x) = 1\), which means
\[
b^{-1}(x) = a(x) \mod m(x).
\]
Moreover, for any \(a(x), b(x)\) and \(c(x)\) in the field, it holds that
\[
a(x) \cdot (b(x) + c(x)) = a(x) \cdot b(x) + a(x) \cdot c(x).
\]
It follows that the set of 256 possible byte values, with XOR used as addition and the multiplication defined as above, has the structure of the finite field \(GF(2^8)\).

### 4.2.1 Multiplication by \(x\)

Multiplying the binary polynomial defined in equation (3.1) with the polynomial \(x\) results in
\[
b_7x^8 + b_6x^7 + b_5x^6 + b_4x^5 + b_3x^4 + b_2x^3 + b_1x^2 + b_0x.
\]
The result \(x \cdot b(x)\) is obtained by reducing the above result modulo \(m(x)\), as defined in equation (4.1). If \(b_7 = 0\), the result is already in reduced form. If \(b_7 = 1\), the reduction is accomplished by subtracting (i.e., XORing) the polynomial \(m(x)\). It follows that multiplication by \(x\) (i.e., \{00000010\} or \{02\}) can be implemented at the byte level as a left shift and a subsequent conditional bitwise XOR with \{1b\}. This operation on bytes is denoted by \texttt{xtime()}.

Multiplication by higher powers of \(x\) can be implemented by repeated application of \texttt{xtime()}. By adding intermediate results, multiplication by any constant can be implemented.

For example, \{57\} \cdot \{13\} = \{fe\} because
\{57\} \cdot \{02\} = \textit{xtime}(\{57\}) = \{ae\} \\
\{57\} \cdot \{04\} = \textit{xtime}(\{ae\}) = \{47\} \\
\{57\} \cdot \{08\} = \textit{xtime}(\{47\}) = \{8e\} \\
\{57\} \cdot \{10\} = \textit{xtime}(\{8e\}) = \{07\}, \\

thus, \\
\{57\} \cdot \{13\} = \{57\} \cdot (\{01\} \oplus \{02\} \oplus \{10\}) \\
= \{57\} \oplus \{ae\} \oplus \{07\} \\
= \{fe\}.

### 4.3 Polynomials with Coefficients in GF(2^8)

Four-term polynomials can be defined - with coefficients that are finite field elements - as:

\[
a(x) = a_3 x^3 + a_2 x^2 + a_1 x + a_0
\]  
(4.5)

which will be denoted as a word in the form \([a_0, a_1, a_2, a_3]\). Note that the polynomials in this section behave somewhat differently than the polynomials used in the definition of finite field elements, even though both types of polynomials use the same indeterminate, \(x\). The coefficients in this section are themselves finite field elements, i.e., bytes, instead of bits; also, the multiplication of four-term polynomials uses a different reduction polynomial, defined below. The distinction should always be clear from the context.

To illustrate the addition and multiplication operations, let

\[
b(x) = b_3 x^3 + b_2 x^2 + b_1 x + b_0 
\]  
(4.6)

define a second four-term polynomial. Addition is performed by adding the finite field coefficients of like powers of \(x\). This addition corresponds to an XOR operation between the corresponding bytes in each of the words – in other words, the XOR of the complete word values.

Thus, using the equations of (4.5) and (4.6),

\[
a(x) + b(x) = (a_3 \oplus b_3) x^3 + (a_2 \oplus b_2) x^2 + (a_1 \oplus b_1) x + (a_0 \oplus b_0) 
\]  
(4.7)

Multiplication is achieved in two steps. In the first step, the polynomial product \(c(x) = a(x) \cdot b(x)\) is algebraically expanded, and like powers are collected to give

\[
c(x) = c_6 x^6 + c_5 x^5 + c_4 x^4 + c_3 x^3 + c_2 x^2 + c_1 x + c_0 
\]  
(4.8)

where

\[
c_0 = a_0 \cdot b_0 \\
c_1 = a_1 \cdot b_0 \oplus a_0 \cdot b_1 \\
c_2 = a_2 \cdot b_0 \oplus a_1 \cdot b_1 \oplus a_0 \cdot b_2 \\
c_3 = a_3 \cdot b_1 \oplus a_2 \cdot b_2 \oplus a_1 \cdot b_3 \\
c_4 = a_3 \cdot b_1 \oplus a_2 \cdot b_2 \oplus a_1 \cdot b_3 \\
c_5 = a_3 \cdot b_2 \oplus a_2 \cdot b_3 \\
c_6 = a_3 \cdot b_3
\]  
(4.9)
\[ c_3 = a_3 \cdot b_0 \oplus a_2 \cdot b_1 \oplus a_1 \cdot b_2 \oplus a_0 \cdot b_3. \]

The result, \( c(x) \), does not represent a four-byte word. Therefore, the second step of the multiplication is to reduce \( c(x) \) modulo a polynomial of degree 4; the result can be reduced to a polynomial of degree less than 4. **For the AES algorithm, this is accomplished with the polynomial \( x^4 + 1 \), so that**

\[ x^i \mod(x^4 + 1) = x^{i \mod 4}. \]  

(4.10)

The modular product of \( a(x) \) and \( b(x) \), denoted by \( a(x) \otimes b(x) \), is given by the four-term polynomial \( d(x) \), defined as follows:

\[ d(x) = d_3 x^3 + d_2 x^2 + d_1 x + d_0 \]  

(4.11)

with

\[
\begin{align*}
  d_0 &= (a_0 \cdot b_0) \oplus (a_3 \cdot b_1) \oplus (a_2 \cdot b_2) \oplus (a_1 \cdot b_3) \\
  d_1 &= (a_1 \cdot b_0) \oplus (a_0 \cdot b_1) \oplus (a_3 \cdot b_2) \oplus (a_2 \cdot b_3) \\
  d_2 &= (a_2 \cdot b_0) \oplus (a_1 \cdot b_1) \oplus (a_0 \cdot b_2) \oplus (a_3 \cdot b_3) \\
  d_3 &= (a_3 \cdot b_0) \oplus (a_2 \cdot b_1) \oplus (a_1 \cdot b_2) \oplus (a_0 \cdot b_3)
\end{align*}
\]  

(4.12)

When \( a(x) \) is a fixed polynomial, the operation defined in equation (4.11) can be written in matrix form as:

\[
\begin{bmatrix}
  d_0 \\
  d_1 \\
  d_2 \\
  d_3
\end{bmatrix} =
\begin{bmatrix}
  a_0 & a_3 & a_2 & a_1 \\
  a_1 & a_0 & a_3 & a_2 \\
  a_2 & a_1 & a_0 & a_3 \\
  a_3 & a_2 & a_1 & a_0
\end{bmatrix}
\begin{bmatrix}
  b_0 \\
  b_1 \\
  b_2 \\
  b_3
\end{bmatrix}
\]  

(4.13)

Because \( x^4 + 1 \) is not an irreducible polynomial over \( GF(2^8) \), multiplication by a fixed four-term polynomial is not necessarily invertible. However, the AES algorithm specifies a fixed four-term polynomial that **does** have an inverse (see Sec. 5.1.3 and Sec. 5.3.3):

\[ a(x) = \{03\}x^3 + \{01\}x^2 + \{01\}x + \{02\} \]  

(4.14)

\[ a^{-1}(x) = \{0b\}x^3 + \{0d\}x^2 + \{09\}x + \{0e\}. \]  

(4.15)

Another polynomial used in the AES algorithm (see the RotWord() function in Sec. 5.2) has \( a_0 = a_1 = a_2 = \{00\} \) and \( a_3 = \{01\} \), which is the polynomial \( x^3 \). Inspection of equation (4.13) above will show that its effect is to form the output word by rotating bytes in the input word. This means that \([b_0, b_1, b_2, b_3]\) is transformed into \([b_1, b_2, b_3, b_0] \).

---

### 5. Algorithm Specification

For the AES algorithm, **the length of the input block, the output block and the State is 128 bits.** This is represented by \( Nb = 4 \), which reflects the number of 32-bit words (number of columns) in the State.
For the AES algorithm, the length of the Cipher Key, $K$, is 128, 192, or 256 bits. The key length is represented by $N_k = 4, 6, \text{ or } 8$, which reflects the number of 32-bit words (number of columns) in the Cipher Key.

For the AES algorithm, the number of rounds to be performed during the execution of the algorithm is dependent on the key size. The number of rounds is represented by $N_r$, where $N_r = 10$ when $N_k = 4$, $N_r = 12$ when $N_k = 6$, and $N_r = 14$ when $N_k = 8$.

The only Key-Block-Round combinations that conform to this standard are given in Fig. 4. For implementation issues relating to the key length, block size and number of rounds, see Sec. 6.3.

<table>
<thead>
<tr>
<th>Key Length $(N_k \text{ words})$</th>
<th>Block Size $(N_b \text{ words})$</th>
<th>Number of Rounds $(N_r)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>AES-128</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>AES-192</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td>AES-256</td>
<td>8</td>
<td>14</td>
</tr>
</tbody>
</table>

Figure 4. Key-Block-Round Combinations.

For both its Cipher and Inverse Cipher, the AES algorithm uses a round function that is composed of four different byte-oriented transformations: 1) byte substitution using a substitution table (S-box), 2) shifting rows of the State array by different offsets, 3) mixing the data within each column of the State array, and 4) adding a Round Key to the State. These transformations (and their inverses) are described in Sec. 5.1.1-5.1.4 and 5.3.1-5.3.4.

The Cipher and Inverse Cipher are described in Sec. 5.1 and Sec. 5.3, respectively, while the Key Schedule is described in Sec. 5.2.

5.1 Cipher

At the start of the Cipher, the input is copied to the State array using the conventions described in Sec. 3.4. After an initial Round Key addition, the State array is transformed by implementing a round function 10, 12, or 14 times (depending on the key length), with the final round differing slightly from the first $N_r - 1$ rounds. The final State is then copied to the output as described in Sec. 3.4.

The round function is parameterized using a key schedule that consists of a one-dimensional array of four-byte words derived using the Key Expansion routine described in Sec. 5.2.

The Cipher is described in the pseudo code in Fig. 5. The individual transformations - SubBytes(), ShiftRows(), MixColumns(), and AddRoundKey() – process the State and are described in the following subsections. In Fig. 5, the array $w[]$ contains the key schedule, which is described in Sec. 5.2.

As shown in Fig. 5, all $N_r$ rounds are identical with the exception of the final round, which does not include the MixColumns() transformation.
Appendix B presents an example of the Cipher, showing values for the State array at the beginning of each round and after the application of each of the four transformations described in the following sections.

```plaintext
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])    // See Sec. 5.1.4
  for round = 1 step 1 to Nr-1
    SubBytes(state)                // See Sec. 5.1.1
    ShiftRows(state)               // See Sec. 5.1.2
    MixColumns(state)              // See Sec. 5.1.3
    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
```

**Figure 5. Pseudo Code for the Cipher.**

5.1.1 SubBytes() Transformation

The SubBytes() transformation is a non-linear byte substitution that operates independently on each byte of the State using a substitution table (S-box). This S-box (Fig. 7), which is invertible, is constructed by composing two transformations:

1. Take the multiplicative inverse in the finite field GF(2^8), described in Sec. 4.2; the element {00} is mapped to itself.

2. Apply the following affine transformation (over GF(2)):

   \[ b'_i = b_i \oplus b_{(i+4)\text{mod }8} \oplus b_{(i+5)\text{mod }8} \oplus b_{(i+6)\text{mod }8} \oplus b_{(i+7)\text{mod }8} \oplus c_i \quad (5.1) \]

   for \(0 \leq i < 8\), where \(b_i\) is the \(i^{th}\) bit of the byte, and \(c_i\) is the \(i^{th}\) bit of a byte \(c\) with the value \{63\} or \{01100011\}. Here and elsewhere, a prime on a variable (e.g., \(b'_i\)) indicates that the variable is to be updated with the value on the right.

   In matrix form, the affine transformation element of the S-box can be expressed as:

---

1 The various transformations (e.g., SubBytes(), ShiftRows(), etc.) act upon the State array that is addressed by the 'state' pointer. AddRoundKey() uses an additional pointer to address the Round Key.
Figure 6 illustrates the effect of the SubBytes() transformation on the State.

The S-box used in the SubBytes() transformation is presented in hexadecimal form in Fig. 7. For example, if \( s_{i,1} = \{53\} \), then the substitution value would be determined by the intersection of the row with index ‘5’ and the column with index ‘3’ in Fig. 7. This would result in \( s'_{i,1} \) having a value of \{ed\}.

![S-Box Diagram](image_url)

**Figure 6.** SubBytes() applies the S-box to each byte of the State.

**Figure 7.** S-box: substitution values for the byte \( xy \) (in hexadecimal format).
5.1.2 ShiftRows() Transformation

In the ShiftRows() transformation, the bytes in the last three rows of the State are cyclically shifted over different numbers of bytes (offsets). The first row, \( r = 0 \), is not shifted.

Specifically, the ShiftRows() transformation proceeds as follows:

\[
s'_{r,c} = s_{r,(c + \text{shift}(r,Nb)) \mod Nb}
\]

for \( 0 < r < 4 \) and \( 0 \leq c < Nb \), \hspace{1cm} (5.3)

where the shift value \( \text{shift}(r,Nb) \) depends on the row number, \( r \), as follows (recall that \( Nb = 4 \)):

\[
\text{shift}(1,4) = 1; \quad \text{shift}(2,4) = 2; \quad \text{shift}(3,4) = 3.
\]

This has the effect of moving bytes to “lower” positions in the row (i.e., lower values of \( c \) in a given row), while the “lowest” bytes wrap around into the “top” of the row (i.e., higher values of \( c \) in a given row).

Figure 8 illustrates the ShiftRows() transformation.

---

5.1.3 MixColumns() Transformation

The MixColumns() transformation operates on the State column-by-column, treating each column as a four-term polynomial as described in Sec. 4.3. The columns are considered as polynomials over \( GF(2^8) \) and multiplied modulo \( x^4 + 1 \) with a fixed polynomial \( a(x) \), given by

\[
a(x) = \{03\}x^3 + \{01\}x^2 + \{01\}x + \{02\}.
\]

As described in Sec. 4.3, this can be written as a matrix multiplication. Let

\[
s'(x) = a(x) \otimes s(x);
\]
As a result of this multiplication, the four bytes in a column are replaced by the following:

\[
\begin{align*}
    s'_{0,c} & = (\{02\} \cdot s_{0,c}) \oplus (\{03\} \cdot s_{1,c}) \oplus s_{2,c} \oplus s_{3,c} \\
    s'_{1,c} & = s_{0,c} \oplus (\{02\} \cdot s_{1,c}) \oplus (\{03\} \cdot s_{2,c}) \oplus s_{3,c} \\
    s'_{2,c} & = s_{0,c} \oplus s_{1,c} \oplus (\{02\} \cdot s_{2,c}) \oplus (\{03\} \cdot s_{3,c}) \\
    s'_{3,c} & = (\{03\} \cdot s_{0,c}) \oplus s_{1,c} \oplus s_{2,c} \oplus (\{02\} \cdot s_{3,c}).
\end{align*}
\]

Figure 9 illustrates the **MixColumns()** transformation.

5.1.4 **AddRoundKey()** Transformation

In the **AddRoundKey()** transformation, a Round Key is added to the State by a simple bitwise XOR operation. Each Round Key consists of \(Nb\) words from the key schedule (described in Sec. 5.2). Those \(Nb\) words are each added into the columns of the State, such that

\[
[s'_{0,c}, s'_{1,c}, s'_{2,c}, s'_{3,c}] = [s_{0,c}, s_{1,c}, s_{2,c}, s_{3,c}] \oplus [w_{\text{round} \times Nb + c}] \quad \text{for} \ 0 \leq c < Nb,
\]

where \([w_i]\) are the key schedule words described in Sec. 5.2, and \(\text{round}\) is a value in the range \(0 \leq \text{round} \leq Nr\). In the Cipher, the initial Round Key addition occurs when \(\text{round} = 0\), prior to the first application of the round function (see Fig. 5). The application of the **AddRoundKey()** transformation to the \(Nr\) rounds of the Cipher occurs when \(1 \leq \text{round} \leq Nr\).

The action of this transformation is illustrated in Fig. 10, where \(l = \text{round} \times Nb\). The byte address within words of the key schedule was described in Sec. 3.1.
5.2 Key Expansion

The AES algorithm takes the Cipher Key, \( K \), and performs a Key Expansion routine to generate a key schedule. The Key Expansion generates a total of \( Nb \) \((Nr + 1) \) words: the algorithm requires an initial set of \( Nb \) words, and each of the \( Nr \) rounds requires \( Nb \) words of key data. The resulting key schedule consists of a linear array of 4-byte words, denoted \([w_i]\), with \( i \) in the range \( 0 \leq i < Nb(Nr + 1) \).

The expansion of the input key into the key schedule proceeds according to the pseudo code in Fig. 11.

SubWord() is a function that takes a four-byte input word and applies the S-box (Sec. 5.1.1, Fig. 7) to each of the four bytes to produce an output word. The function RotWord() takes a word \([a_0, a_1, a_2, a_3]\) as input, performs a cyclic permutation, and returns the word \([a_1, a_2, a_3, a_0]\). The round constant word array, Rcon[i], contains the values given by \([x^{i-1}, {00}, {00}, {00}]\), with \( x^{i-1} \) being powers of \( x \) (\( x \) is denoted as \( \{02\} \)) in the field \( GF(2^8) \), as discussed in Sec. 4.2 (note that \( i \) starts at 1, not 0).

From Fig. 11, it can be seen that the first \( Nk \) words of the expanded key are filled with the Cipher Key. Every following word, \( w[i] \), is equal to the XOR of the previous word, \( w[i-1] \), and the word \( Nk \) positions earlier, \( w[i-Nk] \). For words in positions that are a multiple of \( Nk \), a transformation is applied to \( w[i-1] \) prior to the XOR, followed by an XOR with a round constant, Rcon[i]. This transformation consists of a cyclic shift of the bytes in a word (RotWord()), followed by the application of a table lookup to all four bytes of the word (SubWord()).

It is important to note that the Key Expansion routine for 256-bit Cipher Keys (\( Nk = 8 \)) is slightly different than for 128- and 192-bit Cipher Keys. If \( Nk = 8 \) and \( i-4 \) is a multiple of \( Nk \), then SubWord() is applied to \( w[i-1] \) prior to the XOR.
KeyExpansion(byte key[4*Nk], word w[Nb*(Nr+1)], Nk)
begin
   word temp

   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])
      temp = w[i-1]
      if (i mod Nk = 0)
         temp = SubWord(RotWord(temp)) xor Rcon[i/Nk]
      else if (Nk > 6 and i mod Nk = 4)
         temp = SubWord(temp)
      end if
      w[i] = w[i-Nk] xor temp
      i = i + 1
   end while
end

Note that Nk=4, 6, and 8 do not all have to be implemented; they are all included in the conditional statement above for conciseness. Specific implementation requirements for the Cipher Key are presented in Sec. 6.1.

Figure 11. Pseudo Code for Key Expansion.²

Appendix A presents examples of the Key Expansion.

5.3 Inverse Cipher

The Cipher transformations in Sec. 5.1 can be inverted and then implemented in reverse order to produce a straightforward Inverse Cipher for the AES algorithm. The individual transformations used in the Inverse Cipher - InvShiftRows(), InvSubBytes(), InvMixColumns(), and AddRoundKey() – process the State and are described in the following subsections.

The Inverse Cipher is described in the pseudo code in Fig. 12. In Fig. 12, the array w[] contains the key schedule, which was described previously in Sec. 5.2.

² The functions SubWord() and RotWord() return a result that is a transformation of the function input, whereas the transformations in the Cipher and Inverse Cipher (e.g., ShiftRows(), SubBytes(), etc.) transform the State array that is addressed by the ‘state’ pointer.
InvCipher(byte in[4*Nb], byte out[4*Nb], word w[Nb*(Nr+1)])
begin
    byte state[4,Nb]

    state = in

    AddRoundKey(state, w[Nr*Nb, (Nr+1)*Nb-1]) // See Sec. 5.1.4

    for round = Nr-1 step -1 downto 1
        InvShiftRows(state) // See Sec. 5.3.1
        InvSubBytes(state) // See Sec. 5.3.2
        AddRoundKey(state, w[round*Nb, (round+1)*Nb-1])
        InvMixColumns(state) // See Sec. 5.3.3
    end for

    InvShiftRows(state)
    InvSubBytes(state)
    AddRoundKey(state, w[0, Nb-1])

    out = state
end

Figure 12. Pseudo Code for the Inverse Cipher.

5.3.1 InvShiftRows() Transformation

InvShiftRows() is the inverse of the ShiftRows() transformation. The bytes in the last three rows of the State are cyclically shifted over different numbers of bytes (offsets). The first row, \( r = 0 \), is not shifted. The bottom three rows are cyclically shifted by \( Nb - shift(r,Nb) \) bytes, where the shift value \( shift(r,Nb) \) depends on the row number, and is given in equation (5.4) (see Sec. 5.1.2).

Specifically, the InvShiftRows() transformation proceeds as follows:

\[
S_{r,c+shift(r,Nb)) \mod Nb} = s_{r,c} \text{ for } 0 < r < 4 \text{ and } 0 \leq c < Nb \quad (5.8)
\]

Figure 13 illustrates the InvShiftRows() transformation.

---

3 The various transformations (e.g., InvSubBytes(), InvShiftRows(), etc.) act upon the State array that is addressed by the 'state' pointer. AddRoundKey() uses an additional pointer to address the Round Key.
5.3.2 InvSubBytes() Transformation

InvSubBytes() is the inverse of the byte substitution transformation, in which the inverse S-box is applied to each byte of the State. This is obtained by applying the inverse of the affine transformation (5.1) followed by taking the multiplicative inverse in GF($2^8$).

The inverse S-box used in the InvSubBytes() transformation is presented in Fig. 14:

![Inverse S-box](image)

**Figure 14.** Inverse S-box: substitution values for the byte $x_y$ (in hexadecimal format). 

![InverShiftRows](image)

**Figure 13.** InvShiftRows() cyclically shifts the last three rows in the State.
5.3.3 InvMixColumns() Transformation

InvMixColumns() is the inverse of the MixColumns() transformation. InvMixColumns() operates on the State column-by-column, treating each column as a four-term polynomial as described in Sec. 4.3. The columns are considered as polynomials over GF(2^8) and multiplied modulo x^4 + 1 with a fixed polynomial a^{-1}(x), given by

\[ a^{-1}(x) = \{0b\}x^3 + \{0d\}x^2 + \{09\}x + \{0e\}. \quad (5.9) \]

As described in Sec. 4.3, this can be written as a matrix multiplication. Let

\[
\begin{pmatrix}
    s_{0,c}' \\
    s_{1,c}' \\
    s_{2,c}' \\
    s_{3,c}'
\end{pmatrix} =
\begin{bmatrix}
    0e & 0b & 0d & 09 \\
    09 & 0e & 0b & 0d \\
    0d & 09 & 0e & 0b \\
    0b & 0d & 09 & 0e
\end{bmatrix}
\begin{pmatrix}
    s_{0,c} \\
    s_{1,c} \\
    s_{2,c} \\
    s_{3,c}
\end{pmatrix}
\text{ for } 0 \leq c < Nb. \quad (5.10)
\]

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

\[
\begin{align*}
    s_{0,c}' &= (\{0e\} \cdot s_{0,c} + \{0b\} \cdot s_{1,c} + \{0d\} \cdot s_{2,c} + \{09\} \cdot s_{3,c}) \\
    s_{1,c}' &= (\{09\} \cdot s_{0,c} + \{0e\} \cdot s_{1,c} + \{0b\} \cdot s_{2,c} + \{0d\} \cdot s_{3,c}) \\
    s_{2,c}' &= (\{0d\} \cdot s_{0,c} + \{09\} \cdot s_{1,c} + \{0e\} \cdot s_{2,c} + \{0b\} \cdot s_{3,c}) \\
    s_{3,c}' &= (\{0b\} \cdot s_{0,c} + \{0d\} \cdot s_{1,c} + \{09\} \cdot s_{2,c} + \{0e\} \cdot s_{3,c})
\end{align*}
\]

5.3.4 Inverse of the AddRoundKey() Transformation

AddRoundKey(), which was described in Sec. 5.1.4, is its own inverse, since it only involves an application of the XOR operation.

5.3.5 Equivalent Inverse Cipher

In the straightforward Inverse Cipher presented in Sec. 5.3 and Fig. 12, the sequence of the transformations differs from that of the Cipher, while the form of the key schedules for encryption and decryption remains the same. However, several properties of the AES algorithm allow for an Equivalent Inverse Cipher that has the same sequence of transformations as the Cipher (with the transformations replaced by their inverses). This is accomplished with a change in the key schedule.

The two properties that allow for this Equivalent Inverse Cipher are as follows:

1. The SubBytes() and ShiftRows() transformations commute; that is, a SubBytes() transformation immediately followed by a ShiftRows() transformation is equivalent to a ShiftRows() transformation immediately followed by a SubBytes() transformation. The same is true for their inverses, InvSubBytes() and InvShiftRows.
2. The column mixing operations - `MixColumns()` and `InvMixColumns()` - are linear with respect to the column input, which means

\[
\text{InvMixColumns(state XOR Round Key)} = \text{InvMixColumns(state)} \text{ XOR InvMixColumns(Round Key)}.
\]

These properties allow the order of `InvSubBytes()` and `InvShiftRows()` transformations to be reversed. The order of the `AddRoundKey()` and `InvMixColumns()` transformations can also be reversed, provided that the columns (words) of the decryption key schedule are modified using the `InvMixColumns()` transformation.

The equivalent inverse cipher is defined by reversing the order of the `InvSubBytes()` and `InvShiftRows()` transformations shown in Fig. 12, and by reversing the order of the `AddRoundKey()` and `InvMixColumns()` transformations used in the “round loop” after first modifying the decryption key schedule for `round = 1` to `Nr-1` using the `InvMixColumns()` transformation. The first and last `Nb` words of the decryption key schedule shall not be modified in this manner.

Given these changes, the resulting Equivalent Inverse Cipher offers a more efficient structure than the Inverse Cipher described in Sec. 5.3 and Fig. 12. Pseudo code for the Equivalent Inverse Cipher appears in Fig. 15. (The word array `dw[]` contains the modified decryption key schedule. The modification to the Key Expansion routine is also provided in Fig. 15.)
```
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, (Nr+1)*Nb-1])
    for round = Nr-1 step -1 downto 1
        InvSubBytes(state)
        InvShiftRows(state)
        InvMixColumns(state)
        AddRoundKey(state, dw[round*Nb, (round+1)*Nb-1])
    end for
    InvSubBytes(state)
    InvShiftRows(state)
    AddRoundKey(state, dw[0, Nb-1])
    out = state
end
```

For the Equivalent Inverse Cipher, the following pseudo code is added at the end of the Key Expansion routine (Sec. 5.2):

```
for i = 0 step 1 to (Nr+1)*Nb-1
    dw[i] = w[i]
end for

for round = 1 step 1 to Nr-1
    InvMixColumns(dw[round*Nb, (round+1)*Nb-1])  // note change of type
end for
```

Note that, since InvMixColumns operates on a two-dimensional array of bytes while the Round Keys are held in an array of words, the call to InvMixColumns in this code sequence involves a change of type (i.e. the input to InvMixColumns() is normally the State array, which is considered to be a two-dimensional array of bytes, whereas the input here is a Round Key computed as a one-dimensional array of words).

---

**Figure 15. Pseudo Code for the Equivalent Inverse Cipher.**

6. Implementation Issues

6.1 Key Length Requirements

An implementation of the AES algorithm shall support *at least one* of the three key lengths specified in Sec. 5: 128, 192, or 256 bits (i.e., $Nk = 4, 6, \text{ or } 8, \text{ respectively}$). Implementations
may optionally support two or three key lengths, which may promote the interoperability of algorithm implementations.

6.2 Keying Restrictions

No weak or semi-weak keys have been identified for the AES algorithm, and there is no restriction on key selection.

6.3 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 \( N_r \) – see Fig. 4. 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.

6.4 Implementation Suggestions Regarding Various Platforms

Implementation variations are possible that may, in many cases, offer performance or other advantages. Given the same input key and data (plaintext or ciphertext), any implementation that produces the same output (ciphertext or plaintext) as the algorithm specified in this standard is an acceptable implementation of the AES.

Reference [3] and other papers located at Ref. [1] include suggestions on how to efficiently implement the AES algorithm on a variety of platforms.
Appendix A - Key Expansion Examples

This appendix shows the development of the key schedule for various key sizes. Note that multi-byte values are presented using the notation described in Sec. 3. The intermediate values produced during the development of the key schedule (see Sec. 5.2) are given in the following table (all values are in hexadecimal format, with the exception of the index column (i)).

A.1 Expansion of a 128-bit Cipher Key

This section contains the key expansion of the following cipher key:

\[
\text{Cipher Key} = \text{2b 7e 15 16 28 ae d2 a6 ab f7 15 88 09 cf 4f 3c}
\]

for \(Nk = 4\), which results in

\[
\begin{align*}
w_0 &= \text{2b7e1516} \\
w_1 &= \text{28aed2a6} \\
w_2 &= \text{abf71588} \\
w_3 &= \text{09cf4f3c}
\end{align*}
\]
### A.2 Expansion of a 192-bit Cipher Key

This section contains the key expansion of the following cipher key:

\[
\text{Cipher Key} = \begin{array}{cccccccccccc}
8 & e & 7 & 3 & b & 0 & f & 7 & d & a & 0 & e & 6 & 4 & 5 & 2 & c & 8 & 1 & 0 & f & 3 & 2 & b \\
8 & 0 & 9 & 0 & 7 & 9 & e & 5 & 6 & 2 & f & 8 & e & a & d & 2 & 5 & 2 & c & 6 & b & 7 & b
\end{array}
\]

for \(Nk = 6\), which results in

\[
\begin{align*}
w_0 &= 8e73b0f7 \\
w_1 &= da0e6452 \\
w_2 &= c810f32b \\
w_3 &= 809079e5 \\
w_4 &= 62f8ead2 \\
w_5 &= 522c6b7b
\end{align*}
\]

<table>
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<tr>
<th>(i)</th>
<th>(temp)</th>
<th>After RotWord()</th>
<th>After SubWord()</th>
<th>Rcon[i/Nk]</th>
<th>After XOR with Rcon</th>
<th>w[i–Nk]</th>
<th>w[i]=temp XOR w[i–Nk]</th>
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29
### A.3 Expansion of a 256-bit Cipher Key

This section contains the key expansion of the following cipher key:

\[
\text{Cipher Key} = \begin{array}{ccccccccccccccccc}
60 & 3d & eb & 10 & 15 & ca & 71 & be & 2b & 73 & ae & f0 & 85 & 7d & 77 & 81 \\
1f & 35 & 2c & 07 & 3b & 61 & 08 & d7 & 2d & 98 & 10 & a3 & 09 & 14 & df & f4
\end{array}
\]

for \( Nk = 8 \), which results in

\[
\begin{align*}
w_0 &= 603deb10 & w_1 &= 15ca71be & w_2 &= 2b73aef0 & w_3 &= 857d7781 \\
w_4 &= 1f352c07 & w_5 &= 3b6108d7 & w_6 &= 2d9810a3 & w_7 &= 0914dff4
\end{align*}
\]

<table>
<thead>
<tr>
<th>( i ) (dec)</th>
<th>temp</th>
<th>After RotWord()</th>
<th>After SubWord()</th>
<th>RCon[( i/Nk )]</th>
<th>After XOR with Rcon</th>
<th>w[( i-Nk )] = temp XOR w[( i )]</th>
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<th>( i ) (dec)</th>
<th>temp</th>
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<th>After SubWord()</th>
<th>RCon[( i/Nk )]</th>
<th>After XOR with Rcon</th>
<th>w[( i-Nk )] = temp XOR w[( i )]</th>
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Appendix B – Cipher Example

The following diagram shows the values in the State array as the Cipher progresses for a block length and a Cipher Key length of 16 bytes each (i.e., \(N_b = 4\) and \(N_k = 4\)).

**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

The Round Key values are taken from the Key Expansion example in Appendix A.

<table>
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<tr>
<th>Round Number</th>
<th>Start of Round</th>
<th>After SubBytes</th>
<th>After ShiftRows</th>
<th>After MixColumns</th>
<th>Round Key Value</th>
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<td>ac ef 13 45</td>
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<td>a1 78 10 4c</td>
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<td>6d 11 db ca</td>
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<td>83 43 b5 ab</td>
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<td>fe c8 c0 4d</td>
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| 10 | 39 02 dc 19 | 25 dc 11 6a | 84 09 85 0b | 1d 1b 97 32 | 34 |
Appendix C – Example Vectors

This appendix contains example vectors, including intermediate values – for all three AES key lengths \((N_k = 4, 6, \text{ and } 8)\), for the Cipher, Inverse Cipher, and Equivalent Inverse Cipher that are described in Sec. 5.1, 5.3, and 5.3.5, respectively. Additional examples may be found at [1] and [5].

All vectors are in hexadecimal notation, with each pair of characters giving a byte value in which the left character of each pair provides the bit pattern for the 4 bit group containing the higher numbered bits using the notation explained in Sec. 3.2, while the right character provides the bit pattern for the lower-numbered bits. The array index for all bytes (groups of two hexadecimal digits) within these test vectors starts at zero and increases from left to right.

Legend for CIPHER (ENCRYPT) (round number \(r = 0\) to 10, 12 or 14):

- input: cipher input
- start: state at start of round\([r]\)
- s_box: state after SubBytes()
- s_row: state after ShiftRows()
- m_col: state after MixColumns()
- k_sch: key schedule value for round\([r]\)
- output: cipher output

Legend for INVERSE CIPHER (DECRYPT) (round number \(r = 0\) to 10, 12 or 14):

- iinput: inverse cipher input
- istart: state at start of round\([r]\)
- is_box: state after InvSubBytes()
- is_row: state after InvShiftRows()
- ik_sch: key schedule value for round\([r]\)
- ik_add: state after AddRoundKey()
- ioutput: inverse cipher output

Legend for EQUIVALENT INVERSE CIPHER (DECRYPT) (round number \(r = 0\) to 10, 12 or 14):

- iinput: inverse cipher input
- istart: state at start of round\([r]\)
- is_box: state after InvSubBytes()
- is_row: state after InvShiftRows()
- im_col: state after InvMixColumns()
- ik_sch: key schedule value for round\([r]\)
- ioutput: inverse cipher output

C.1 AES-128 \((N_k=4, N_r=10)\)

PLAINTEXT: 00112233445566778899aabbccddeeff
KEY: 000102030405060708090a0b0c0d0e0f

CIPHER (ENCRYPT):
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<th>Operation</th>
<th>Data</th>
</tr>
</thead>
<tbody>
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<td>input</td>
<td>00112345456677889aabbccddeeff</td>
</tr>
<tr>
<td>0</td>
<td>k_sch</td>
<td>0001203405060708090a0b0c0d0e0f</td>
</tr>
<tr>
<td>1</td>
<td>s_box</td>
<td>63cab7040953d051cd60e07ba70e18c</td>
</tr>
<tr>
<td>1</td>
<td>s_row</td>
<td>6353e08c0960e104cd70b751bacad0e7</td>
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<tr>
<td>1</td>
<td>m_col</td>
<td>5f72641557f5bc92f7be3b291dbf9f1a</td>
</tr>
<tr>
<td>1</td>
<td>k_sch</td>
<td>d6aa7fdd2af72fadaa678f1d6ab7f6e</td>
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<tr>
<td>2</td>
<td>start</td>
<td>89d810e8855ace682d1843d8cb128f4</td>
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<td>s_box</td>
<td>a76ica9b97be8b45d8ada1a611fc97369</td>
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<td>s_row</td>
<td>7abe1a6997ad739db8c9a451f6186b1</td>
</tr>
<tr>
<td>2</td>
<td>m_col</td>
<td>ff8796843l1d86a51645151fa773ad009</td>
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<td>2</td>
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**Inverse Cipher (Decrypt):**

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EQUIVALENT INVERSE CIPHER (DECRYPT):

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round[ 1].istart 7ad5fda789ef4e272bca100b3d9ff59f
round[ 1].is_box bdb52189f261b63d0b107c9e8b6e776e
round[ 1].is_row bd6e7c3df2b5779e0b61216e8b10b689
round[ 1].im_col 4773b91ff72f354361cb018e1ae6cf2c

round[ 1].is_row 7a9f102789d5f50b2ebeff9fd3dca4e7
round[ 1].is_box bd6e7c3df2b5779e0b61216e8b10b689
round[ 1].ik_sch 54932d1f08557681093ed9cbe2c974e
round[ 1].ik_add e9f74eef023020f61bf2ccf2353c21c7
round[ 2].istart 54d990a16ba09ab596bbf40ea111702f
round[ 2].is_row 5411f4b56bd9700e96a0902fa1bb9a1
round[ 2].is_box fde3bad205e5d0d73547964ef1fe37f1
round[ 2].ik_sch 47438735a41c65b9e016baf4ae6fb7ad2
round[ 2].ik_add baa03de7a1f9b56ed5512c5fa5414d23
round[ 3].istart 3e1c22c0b6fcdf7b78da85067f6170495
round[ 3].is_row 3e175076b61c046786c2295f6a8bfc0
round[ 3].is_box d1876c0f79c4300a4b5594add66ff4f1f
round[ 3].ik_sch 14f9701ae35fe24c8404af4d44e9a0c26
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round[ 10].is_row 63cab7040953d051cd60e0e7a70e81c
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C.2 AES-192 ($N_k=6, N_r=12$)

PLAINTEXT: 00112233445566778899aabccddeeff

KEY: 000102030405060708090a0b0c0d0e0f1011121314151617

CIPHER (ENCRYPT):

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round[ 0].k_sch 000102030405060708090a0b0c0d0e0f
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EQUIVALENT INVERSE CIPHER (DECRYPT):

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round[1].is_row afb73e1b1c1b86122680f1b2b0d585
round[1].im_col 122a02f724ac820605aace51cc7264
round[1].ik_sch c494bfaae6232abdb54c466f3499d
round[2].is_row 88e7f414f532940ec0cd29b606ec4c9
round[2].ioutput 88ec930e5f7f3b6cc32f4906d2941
round[2].im_col 5cc7aeece3c3872194eae5ef8309a93c7
round[2].ik_sch 8fb9999c973b26839c7f9898d56c872
round[3].istart d37e3705907a120821c371e8c6fbb5
round[3].is_row a98ab23696bd43f4bc42e9f006f4d2
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round[4].ik_sch d7e971a17c2a305fc80f7b97f1f
round[5].istart 85e5c8042f861459f3ebca1b277272df
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round[5].im_col c6deb0a7912364a0f55bfe568803ab
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round[6].im_col 592460b244832b2952e0b831923048f1
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round[7].ik_sch c6deb0a7912364a0f55bfe568803ab
round[8].istart 72b86c7c2f0d523e0d0da10450536b
round[8].is_row 7255dad30fb8031000d6c56d40d527c
round[8].im_col e931a88667053f7dccc5194ab5423a2e
round[8].ik_sch dcc1a88667053f7dccc5194ab5423a2e
round[9].istart 0c030d00c01e6221668acc656d3a2c
round[9].is_row 0c030d00c01e6221668acc656d3a2c
round[9].im_col 592460b244832b2952e0b831923048f1
round[9].ik_sch dcc1a88667053f7dccc5194ab5423a2e
C.3 AES-256 ($Nk=8$, $Nr=14$)

**PLAINTEXT:** 00112233445566778899aabbccddeeff

**KEY:** 000102030405060708090a0b0c0d0e0f101112131415161718191a1b1c1d1e1f

**CIPHER (ENCRYPT):**

round[ 0].input 00112233445566778899aabbccddeeff
round[ 0].k_sch 000102030405060708090a0b0c0d0e0f
round[ 0].start 00102030405060708090a0b0c0d0e0f
round[ 1].s_box 63cb7040953d051cd60e0e7ba70e18c
round[ 1].s_row 6353e08c0960e104cd70b751bacad0e7
round[ 1].m_col 5f7261557f5bc9f7e3b291db9f91a
round[ 1].k_sch 101112131415161718191a1b1c1d1e1f
round[ 2].start 4f63760643e0a85eafa7123201a4e705
round[ 2].s_box 84fb386f1ae1a97df5cfd237e49946b
round[ 2].s_row 84efdb61a5c946df9438977cfbace23
round[ 2].m_col bd2a395d2b6ac438d192443e615da195
round[ 2].k_sch a573c29fa176c498a97fc93a572c09c
round[ 3].start 1859fbca28a1c00a078ed8aad4cf62f109
round[ 3].s_box adcb0f257e9c63e0bc557e951c15ef01
round[ 3].s_row ad9c7e017c55ef25bc150fe01cbb6395
round[ 3].m_col 810dce0cc9db571b367c8e881a1b5bd
round[ 3].k_sch 1651a8cd0244beda15da4c1d0640bade
round[ 4].start 975c66c1cb9f3fa8a9328df8ee10f63
round[ 4].s_box 88a33781f7b6d3e93f9e192f76676e76
round[ 4].s_row 88df3bf1f8076783f833c2194a759e
round[ 4].m_col c357aaf28d81abe6fb2755af103a078c0033
round[ 4].k_sch ae87df00ff11b68a68ed5f0b03cf1c97
round[ 5].start 1c05f271a417e04ff921c5c104701554
round[ 5].s_box 9c6b89a349f0e18499fda678f2515920
round[ 5].s_row 9cf0a62049fd59a39591898f426be178
round[ 5].m_col e76a7f87e85f3f57bd64c877
round[ 5].k_sch 6e0f540f2f9275fe85b373b0581d
round[ 6].start 5e73aee11b457b0a2c7bd288ade99fa
round[ 6].s_box 2e5bacf8a6e3a73c68a20a29c0025c970
round[ 6].s_row 2e67a2daf6f83a86ace7c25ba934
round[ 6].m_col b951c33c02e9bd29ae25db1efa08cc77
round[ 6].k_sch c565827fc9a799176f294cce6cd5598b
round[ 7].start 7f07413c8b4e243ec10c815d375d54c
round[ 7].s_box d2c5831a1f2f36b278fe0c4cec9d0329
INVERSE CIPHER (DECRYPT):

round[ 0].ijinput 8ea2b7ca516745bfeafc49904b496089
round[ 0].i.ik_sch 24fc79ccbf0979e9371ac23c36d68de36
round[ 1].i.start aa5e06ee6ee3c56ded68bac2621bebfb
round[ 1].i.is_row aa218b56e5ebeacdd6ecbf26e63c06
round[ 1].i.is_box 627beceb9999d5aaa045ecf423f56da5
round[ 1].i.ik_sch 4e5a6699a9f24fe07e572baacdf8cdea
round[ 2].i.start d133f22a1a2d2a7bfa0f449697c4f3f4d
round[ 2].i.is_row d1ed44fd1a0f3f2afa4ff27b7c332a69
round[ 2].i.is_box 2c21a820306f154ab712c75eee0da04f
round[ 2].i.ik_sch 4e5a6699a9f24fe07e572baacdf8cdea
round[ 3].i.start c4f4d4da0f3f2afa4ff27b7c332a69
round[ 3].i.is_row d133f22a1a2d2a7bfa0f449697c4f3f4d
round[ 3].i.is_box 2c21a820306f154ab712c75eee0da04f
round[ 3].i.ik_sch 4e5a6699a9f24fe07e572baacdf8cdea
round[ 1].i.ik_add 2c21a820306f154ab712c75eee0da04f
round[ 2].i.start d1ed44fd1a0f3f2afa4ff27b7c332a69
round[ 2].i.is_row d133f22a1a2d2a7bfa0f449697c4f3f4d
round[ 2].i.is_box 2c21a820306f154ab712c75eee0da04f
round[ 2].i.ik_sch 4e5a6699a9f24fe07e572baacdf8cdea
round[ 3].i.start c4f4d4da0f3f2afa4ff27b7c332a69
round[ 3].i.is_row d133f22a1a2d2a7bfa0f449697c4f3f4d
round[ 3].i.is_box 2c21a820306f154ab712c75eee0da04f
round[ 3].i.ik_sch 4e5a6699a9f24fe07e572baacdf8cdea
round[ 1].i.is_input 8ea2b7ca516745bfeafc49904b496089
round[ 0].i.start 24fc79ccbf0979e9371ac23c36d68de36
round[ 0].i.is_row aa218b56e5ebeacdd6ecbf26e63c06
round[ 0].i.is_box 627beceb9999d5aaa045ecf423f56da5
round[ 0].i.ik_sch 4e5a6699a9f24fe07e572baacdf8cdea
round[ 1].i.is_add 2c21a820306f154ab712c75eee0da04f
round[ 2].i.start d1ed44fd1a0f3f2afa4ff27b7c332a69
round[ 2].i.is_row d133f22a1a2d2a7bfa0f449697c4f3f4d
round[ 2].i.is_box 2c21a820306f154ab712c75eee0da04f
round[ 2].i.ik_sch 4e5a6699a9f24fe07e572baacdf8cdea
round[ 3].i.is_add f01afafee7a82979d7a5644ab3afef640
round[ 3].i.ik_add af8690415d6edd387e5bfed5c89013
round[ 4].istart 78e2acce741ed5425100c5e0e23b80c7
round[ 4].is_row 783bc54274e280e0511eacc7e200d5ce
round[ 4].is_box c14907f6ca3b3aa070e9aa313b52b5ec
round[ 4].ik_sch 7ccff71cebeb4fe54136ebbf0d261a7df
round[ 4].ik_add bd86f0ea748fc4f4630f11c1e9331233
round[ 5].istart d6f39dda6279bd1430d52a0e513f3fe
round[ 5].is_row d61352d1a6df3a043279d9fee50d9bddd
round[ 5].is_box 4a824851c57e47643de50c2af3e8c9
round[ 5].ik_sch 45f5a66017bd3873000d4d33640a820a
round[ 5].ik_add 0f77ee31d2ccad0c5403a83f4eef964ca3
round[ 6].istart beb50aa6c6ff856126b0d6aff45c25dc4
round[ 6].is_row bec26a12c6b55fff6b80ac450d56a6
round[ 6].is_box 5aa858395fd287d05gae3886f3b9c5
round[ 6].ik_sch 0bd905fc27b0948ad5245a4c18712cf
round[ 6].ik_add 5174c869d9a8435a8b362ca9745eae
round[ 7].istart f6e062f5054789be50497656ed654c
round[ 7].is_row f6e49f50e06576e74245c65058ff
round[ 7].is_box d653a4696ca0bc0f5acaab5db96ce7e7d
round[ 7].ik_sch 3de23a75524775e272bf9eb45407cf39
round[ 7].ik_add ebb919e13ce7c987d75359ed6b9144
round[ 8].istart d22f0c8291f7e031a798d83b2ecc5354c
round[ 8].is_row d2c5831af2f36b7287e0c4ce9d0329
round[ 8].is_box 7f074143cb4e243ec10c815d8375d4c
round[ 8].ik_sch c656827fc9a799176f294ecec6d5598b
round[ 8].ik_add b951c3302e9dbd29ae25cd1f0afac8c7
round[ 9].istart 2e667a2dacf6eef83a86ace7c25ba934
round[ 9].is_row 2e5badcf8a66e9a73ac67a34286ee2d
round[ 9].is_box c357aae11b45b7b0a2c7bd28a0dc99fa
round[ 9].ik_sch 6de1f1486fa54f9275f8eb53738bb18d
round[ 9].ik_add aeb65ba9740f822d73f567b6b4877
round[10].istart 9cf0a62049fd59a399518984f26be178
round[10].is_row 9c6b9a349f0e18499fda678f2515920
round[10].is_box 1c05f271a17e04ff9f215c104701554
round[10].ik_sch ae87df0f00ff11b68a68ed5f03fc1567
round[10].ik_add b2822d81abe6fb275fafa0378c0033
round[11].istart 88db34fb1f807678d3f833c2194a759e
round[11].is_row 88a433781fd75c2d38349e19f876ff
round[11].is_box 975c66c1cb9f3fa8a93a28df8e10f63
round[11].ik_sch 1651a8cd0244beda15da54d1060bade
round[11].ik_add 810dce0cc9db8172b3678c1ee88a1b5bd
round[12].istart ad9c7e017e55ef25bc150fe01cc6b395
round[12].is_row adcb0f257e9c63e0bc557e951c15ef01
round[12].is_box 1859fbc28alc00a078ed8aad042f6109
round[12].ik_sch a573c29fa176c498a97f9ce93a572e09c
round[12].ik_add bd2a93952d6b4ac348d124243e615da195
round[13].istart 841f6db1a5c946fd4938977cfbab23
round[13].is_row 84fb386f1a1ecac97df5cfd237c49946b
round[13].is_box 4f63760643e0aa95efa7213201a4e705
round[13].ik_sch 101112131415161718191a1b1c1d1e1f
round[13].ik_add 5f72641557f5bcb92f7be3b291db9f91a
round[14].istart 6353e08c096e0104cd70b751bacad0e7
round[14].is_row 63cab7040953d051cd60e0e7ba70e18c
round[14].is_box 00102030405060708090a0b0c0d0e0f0
round[14].ik_sch 000102030405060708090a0b0c0d0e0f
round[14].ioutput 00112233445566778899aaabbccddeeff

EQUIVALENT INVERSE CIPHER (DECRYPT):
round[12].istart  ad9c7e017e55ef25bc150fe01ccb6395
round[12].is_box  181c8a098aed61c2782ffba0c45900ad
round[12].is_row  1859fbc28a1c00a078ed8aadc42f6109
round[12].im_col  aec9bda23e7fd8aff96d74525cdce4e7
round[12].ik_sch  2a2840c924234cc026244cc5202748c4
round[13].istart  84e1fd6b1a5c946fdf4938977cfbac23
round[13].is_box  4fe0210543a7e706efa476850163aa32
round[13].is_row  4f63760643e0aa85efa7213201a4e705
round[13].im_col  794cf891177bdf1ddf67a744acd9c4f6
round[13].ik_sch  1a1f181d1e1b1c191217101516131411
round[14].istart  6353e08c0960e104cd70b751bacad0e7
round[14].is_box  0050a0f04090e03080d02070c01060b0
round[14].is_row  00102030405060708090a0b0c0d0e0f
round[14].ik_sch  000102030405060708090a0b0c0d0e0f
round[14].ioutput 00112233445566778899aabbccddeeff
Appendix D - References


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⁴ A complete set of documentation from the AES development effort – including announcements, public comments, analysis papers, conference proceedings, etc. – is available from this site.