Encryption

CS6025 Data Encoding

Yizong Cheng

2-24-15

PENGUIN CLASSICS

EDGAR ALLAN POE

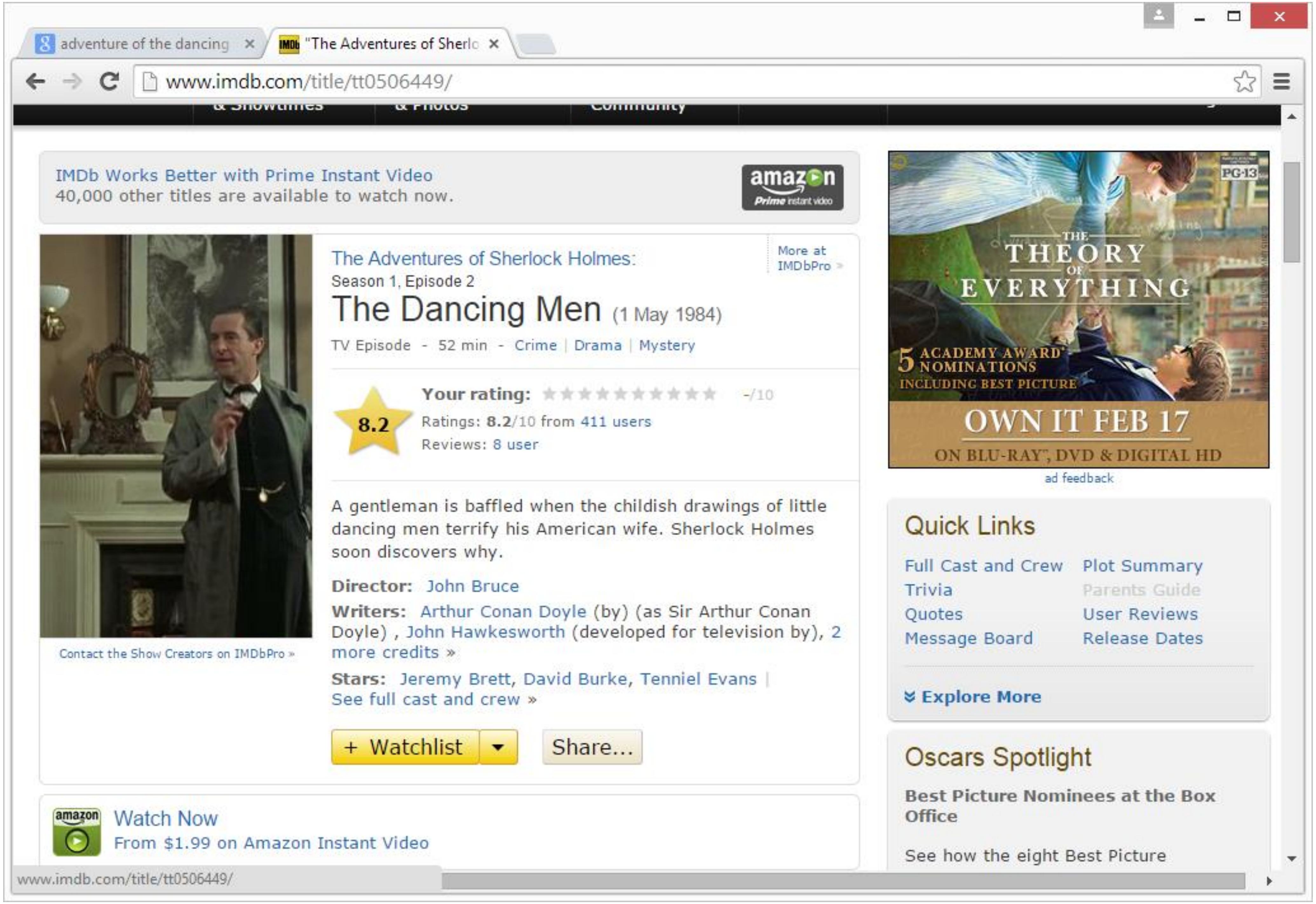
THE FALL OF THE HOUSE OF USHER

AND OTHER WRITINGS

Edgar A. Poe’s “The Gold-Bug” (1843)

53‡‡†305))6*;4826)4‡.)4‡);806*;48†8¶60))85;]8*:‡*8†83(88) 5*†;
46(;88*96*?;8)*‡(;485);5*†2:*‡(;4956*2(5*—4)8¶8*;4069285);)6†8)
4‡‡;1(‡9;48081;8:8‡1;48†85;4)485†528806*81(‡9;48;(88;4(‡?34;48)
4‡;161;:188;‡?;

‘“*A good glass in the bishop’s hostel in the devil’s seat twenty-one degrees and thirteen minutes northeast and by north main branch seventh limb east side shoot from the left eye of the death’s-head a bee-line from the tree through the shot fifty feet out.*”’


adventure of the dancing
"The Adventures of Sherlo
www.imdb.com/title/tt0506449/
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amazon Prime instant video
The Adventures of Sherlock Holmes:
Season 1, Episode 2
The Dancing Men (1 May 1984)
TV Episode - 52 min - Crime | Drama | Mystery
More at IMDbPro »
Your rating: -/10
8.2
Ratings: 8.2/10 from 411 users
Reviews: 8 user
A gentleman is baffled when the childish drawings of little dancing men terrify his American wife. Sherlock Holmes soon discovers why.
Director: John Bruce
Writers: Arthur Conan Doyle (by) (as Sir Arthur Conan Doyle) , John Hawkesworth (developed for television by), 2 more credits »
Stars: Jeremy Brett, David Burke, Tenniel Evans | See full cast and crew »
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THE THEORY OF EVERYTHING
5 ACADEMY AWARD NOMINATIONS
INCLUDING BEST PICTURE
OWN IT FEB 17
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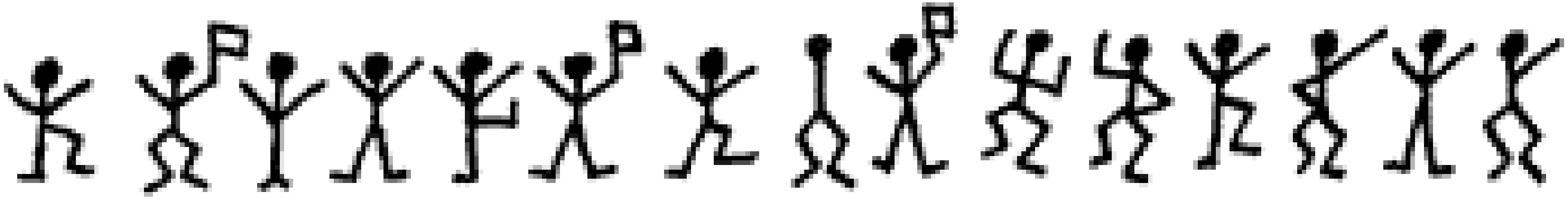
Best Picture Nominees at the Box Office
See how the eight Best Picture
www.imdb.com/title/tt0506449/

The Adventure of the Dancing Men (1898)



Substitute Bytes (SubBytes) in AES

Table 5.2 AES S-Boxes

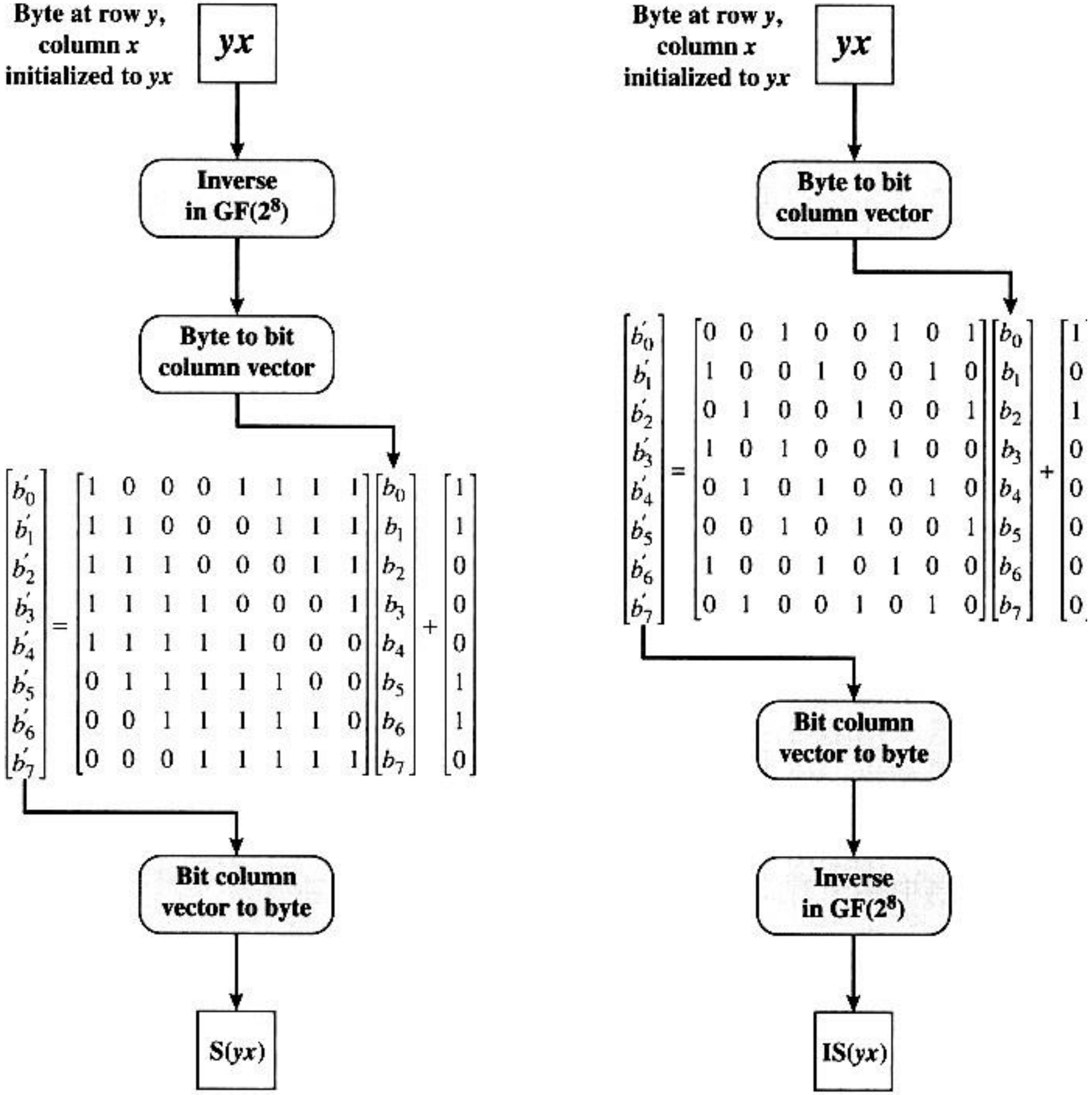
	y																
		0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
x	0	63	7C	77	7B	F2	6B	6F	C5	30	01	67	2B	FE	D7	AB	76
	1	CA	82	C9	7D	FA	59	47	F0	AD	D4	A2	AF	9C	A4	72	C0
	2	B7	FD	93	26	36	3F	F7	CC	34	A5	E5	F1	71	D8	31	15
	3	04	C7	23	C3	18	96	05	9A	07	12	80	E2	EB	27	B2	75
	4	09	83	2C	1A	1B	6E	5A	A0	52	3B	D6	B3	29	E3	2F	84
	5	53	D1	00	ED	20	FC	B1	5B	6A	CB	BE	39	4A	4C	58	CF
	6	D0	EF	AA	FB	43	4D	33	85	45	F9	02	7F	50	3C	9F	A8
	7	51	A3	40	8F	92	9D	38	F5	BC	B6	DA	21	10	FF	F3	D2
	8	CD	0C	13	EC	5F	97	44	17	C4	A7	7E	3D	64	5D	19	73
	9	60	81	4F	DC	22	2A	90	88	46	EE	B8	14	DE	5E	0B	DB
	A	E0	32	3A	0A	49	06	24	5C	C2	D3	AC	62	91	95	E4	79
	B	E7	C8	37	6D	8D	D5	4E	A9	6C	56	F4	EA	65	7A	AE	08
	C	BA	78	25	2E	1C	A6	B4	C6	E8	DD	74	1F	4B	BD	8B	8A
	D	70	3E	B5	66	48	03	F6	0E	61	35	57	B9	86	C1	1D	9E
	E	E1	F8	98	11	69	D9	8E	94	9B	1E	87	E9	CE	55	28	DF
	F	8C	A1	89	0D	BF	E6	42	68	41	99	2D	0F	B0	54	BB	16

(a) S-box

Inverse S-Box for Decoder

x \ y	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
0	52	09	6A	D5	30	36	A5	38	BF	40	A3	9E	81	F3	D7	FB
1	7C	E3	39	82	9B	2F	FF	87	34	8E	43	44	C4	DE	E9	CB
2	54	7B	94	32	A6	C2	23	3D	EE	4C	95	0B	42	FA	C3	4E
3	08	2E	A1	66	28	D9	24	B2	76	5B	A2	49	6D	8B	D1	25
4	72	F8	F6	64	86	68	98	16	D4	A4	5C	CC	5D	65	B6	92
5	6C	70	48	50	FD	ED	B9	DA	5E	15	46	57	A7	8D	9D	84
6	90	D8	AB	00	8C	BC	D3	0A	F7	E4	58	05	B8	B3	45	06
7	D0	2C	1E	8F	CA	3F	0F	02	C1	AF	BD	03	01	13	8A	6B
8	3A	91	11	41	4F	67	DC	EA	97	F2	CF	CE	F0	B4	E6	73
9	96	AC	74	22	E7	AD	35	85	E2	F9	37	E8	1C	75	DF	6E
A	47	F1	1A	71	1D	29	C5	89	6F	B7	62	0E	AA	18	BE	1B
B	FC	56	3E	4B	C6	D2	79	20	9A	DB	C0	FE	78	CD	5A	F4
C	1F	DD	A8	33	88	07	C7	31	B1	12	10	59	27	80	EC	5F
D	60	51	7F	A9	19	B5	4A	0D	2D	E5	7A	9F	93	C9	9C	EF
E	A0	E0	3B	4D	AE	2A	F5	B0	C8	EB	BB	3C	83	53	99	61
F	17	2B	04	7E	BA	77	D6	26	E1	69	14	63	55	21	0C	7D

(b) Inverse S-box



(a) Calculation of byte at row *y*, column *x* of S-box

(a) Calculation of byte at row *y*, column *x* of IS-box

Figure 5.6 Constuction of S-Box and IS-Box

Global Constants and Variables

```
static final int numberOfBits = 8;
static final int fieldSize = 1 << numberOfBits;
static final int irreducible = 0x11b;
static final int logBase = 3;
static final byte[][] A = new byte[][] {
            {1, 1, 1, 1, 1, 0, 0, 0},
            {0, 1, 1, 1, 1, 1, 0, 0},
            {0, 0, 1, 1, 1, 1, 1, 0},
            {0, 0, 0, 1, 1, 1, 1, 1},
            {1, 0, 0, 0, 1, 1, 1, 1},
            {1, 1, 0, 0, 0, 1, 1, 1},
            {1, 1, 1, 0, 0, 0, 1, 1},
            {1, 1, 1, 1, 0, 0, 0, 1}
     };
static final byte[] B = new byte[] { 0, 1, 1, 0, 0, 0, 1, 1};
int[] alog = new int[fieldSize];
int[] log = new int[fieldSize];
int[] S = new int[fieldSize];
```

Making the S-Box

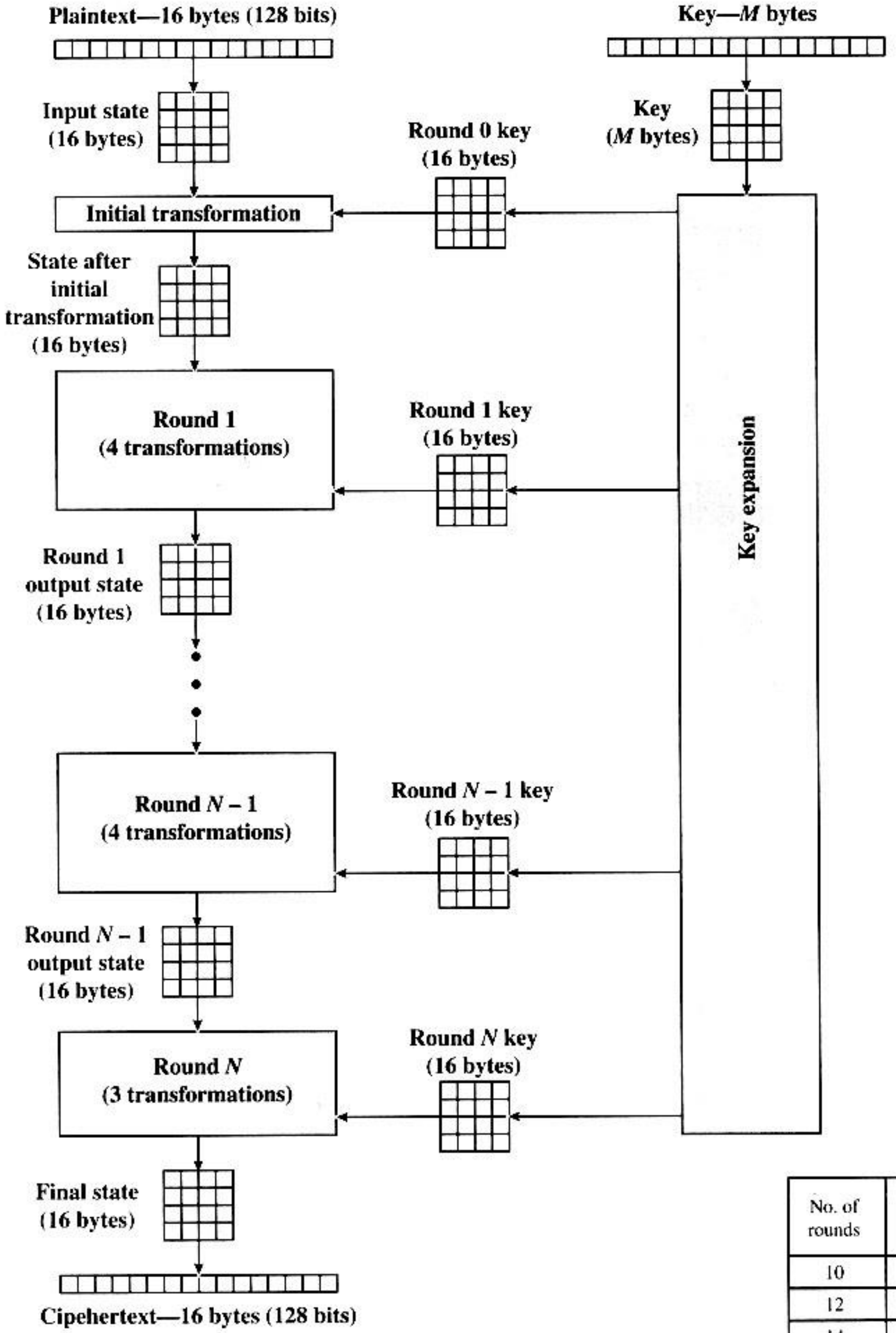
```
void buildS(){
     int[] bitColumn = new int[8];
     for (int i = 0; i < fieldSize; i++){
       int inverse = i < 2 ? i : multiplicativeInverse(i);
       for (int k = 0; k < 8; k++)
           bitColumn[k] = inverse >> (7 - k) & 1;
       S[i] = 0;
       for (int k = 0; k < 8; k++){
          int bit = B[k];
          for (int l = 0; l < 8; l++)
            if (bitColumn[l] == 1) bit ^= A[k][l];
          S[i] ^= bit << 7 - k;
       }
   }
```

Linear Code

- One step in building the S box is $b' = Ab + B$. b', b, and B are vectors in Z_2 and A is a matrix in Z_2.
- The inverse is $b = A'b' + B'$. Substituting $b' = Ab + B$, we have $b = A'Ab + A'B + B'$. The solution is $A'A = I$ and $B' = A'B$.

Advanced Encryption Standard (AES)

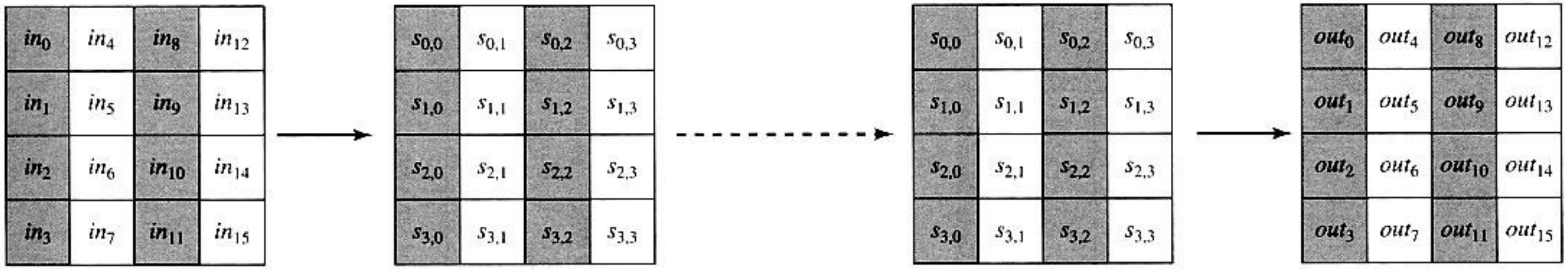
- Adopted and published by NIST 12/4/2001
- Selected from 15 candidate ciphers
- Invented by Belgians Daemen and Rijmen
- Also named Rijindael
- Plaintext/ciphertext element: 16-byte blocks



No. of rounds	Key Length (bytes)
10	16
12	24
14	32

Figure 5.1 AES Encryption Process

The 16-Byte Block and Key



(a) Input, state array, and output

(b) Key and expanded key

Figure 5.2 AES Data Structures

Four Transformations and Iteration

- AddRoundKey (A)
- SubBytes (B)
- ShiftRow (S)
- MixColumn (M)
- ABSMABSMA…BSMABSA
- Initiation: A
- 10 rounds of BSMA
- Final round: BSA

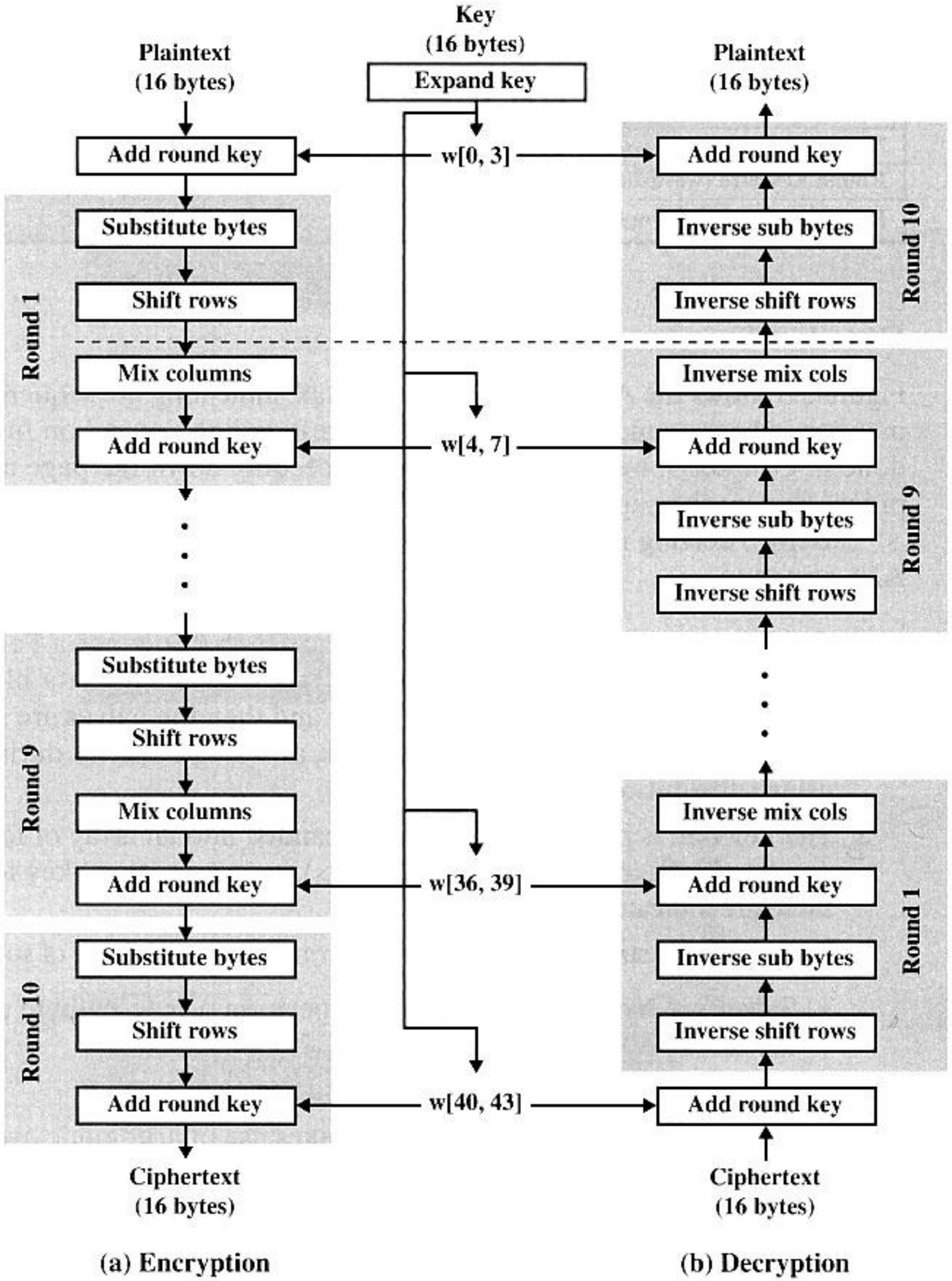


Figure 5.3 AES Encryption and Decryption

```
static final int blockSize = 16;
int[] state = new int[blockSize];

int readBlock(){
 byte[] data = new byte[blockSize];
 int len = 0;
 try {
   len = System.in.read(data);
 } catch (IOException e){
   System.err.println(e.getMessage());
   System.exit(1);
 }
 if (len <= 0) return len;
 for (int i = 0; i < len; i++){
   if (data[i] < 0) state[i] = data[i] + fieldSize;
   else state[i] = data[i];
 }
 for (int i = len; i < blockSize; i++) state[i] = 0;
  return len;
}

void subBytes(){
  for (int i = 0; i < blockSize; i++) state[i] = S[state[i]];
}
```

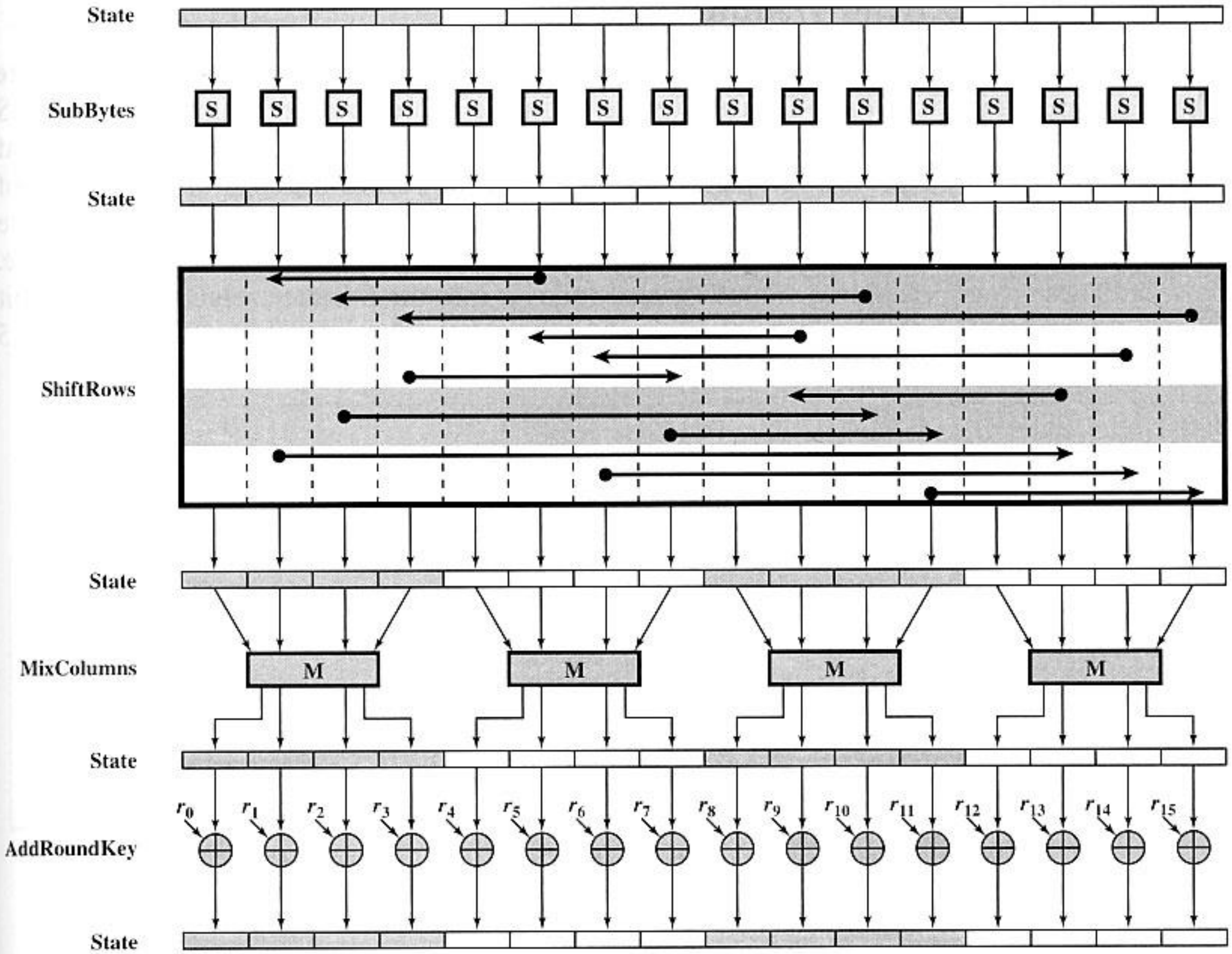


Figure 5.4 AES Encryption Round

Example of SubBytes

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

→

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

Example of ShiftRows

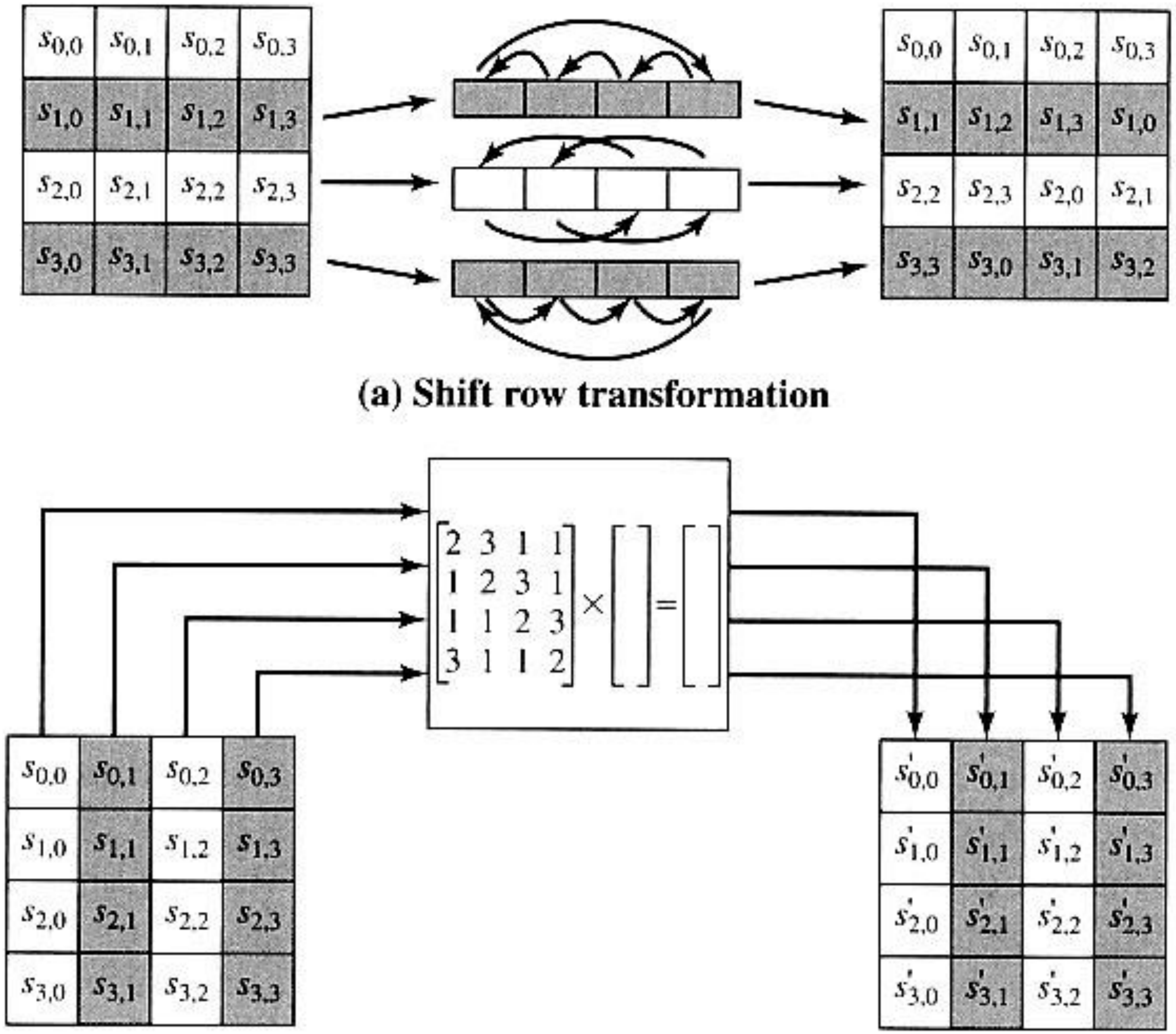
87	F2	4D	97
EC	6E	4C	90
4A	C3	46	E7
8C	D8	95	A6

→

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

Shift Rows

```
void shiftRows(){
  int temp = state[2]; state[2] = state[10]; state[10] = temp;
  temp = state[6]; state[6] = state[14]; state[14] = temp;
  temp = state[1]; state[1] = state[5]; state[5] = state[9];
  state[9] = state[13]; state[13] = temp;
  temp = state[3]; state[3] = state[15]; state[15] = state[11];
  state[11] = state[7]; state[7] = temp;
}
```



(b) Mix column transformation

Figure 5.7 AES Row and Column Operations

MixColumns

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

MixColumns

$$s'_{0,j} = (2 \bullet s_{0,j}) \oplus (3 \bullet s_{1,j}) \oplus s_{2,j} \oplus s_{3,j}$$

$$s'_{1,j} = s_{0,j} \oplus (2 \bullet s_{1,j}) \oplus (3 \bullet s_{2,j}) \oplus s_{3,j}$$

$$s'_{2,j} = s_{0,j} \oplus s_{1,j} \oplus (2 \bullet s_{2,j}) \oplus (3 \bullet s_{3,j})$$

$$s'_{3,j} = (3 \bullet s_{0,j}) \oplus s_{1,j} \oplus s_{2,j} \oplus (2 \bullet s_{3,j})$$

The following is an example of MixColumns:

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

→

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

mixColumns

```
static final byte[][] G = new byte[][] {
            {2, 1, 1, 3},
            {3, 2, 1, 1},
            {1, 3, 2, 1},
            {1, 1, 3, 2}
        };

void mixColumns(){
  int[] temp = new int[4];
  for (int k = 0; k < 4; k++){
   for (int i = 0; i < 4; i++){
     temp[i] = 0;
     for (int j = 0; j < 4; j++)
       temp[i] ^= logMultiply(G[j][i], state[k * 4 + j]);
   }
   for (int i = 0; i < 4; i++) state[k * 4 + i] = temp[i];
  }
 }
```

AddRoundKey (A)

- There are 11 roundKeys from expansion of the 128-bit crypt key
- Each roundKey is byte[16]
- AddRoundKey bitwise XORs the roundKey to the block as byte[16].
- AddRoundKey is its own inverse.

```
void addRoundKey(int round){
   for (int k = 0; k < blockSize; k++)
      state[k] ^= roundKey[round][k];
}
```

AddRoundKey

$$\begin{array}{|c|c|c|c|}\hline 47 & 40 & A3 & 4C \\ \hline 37 & D4 & 70 & 9F \\ \hline 94 & E4 & 3A & 42 \\ \hline ED & A5 & A6 & BC \\ \hline \end{array} \oplus \begin{array}{|c|c|c|c|}\hline AC & 19 & 28 & 57 \\ \hline 77 & FA & D1 & 5C \\ \hline 66 & DC & 29 & 00 \\ \hline F3 & 21 & 41 & 6A \\ \hline \end{array} = \begin{array}{|c|c|c|c|}\hline EB & 59 & 8B & 1B \\ \hline 40 & 2E & A1 & C3 \\ \hline F2 & 38 & 13 & 42 \\ \hline 1E & 84 & E7 & D6 \\ \hline \end{array}$$

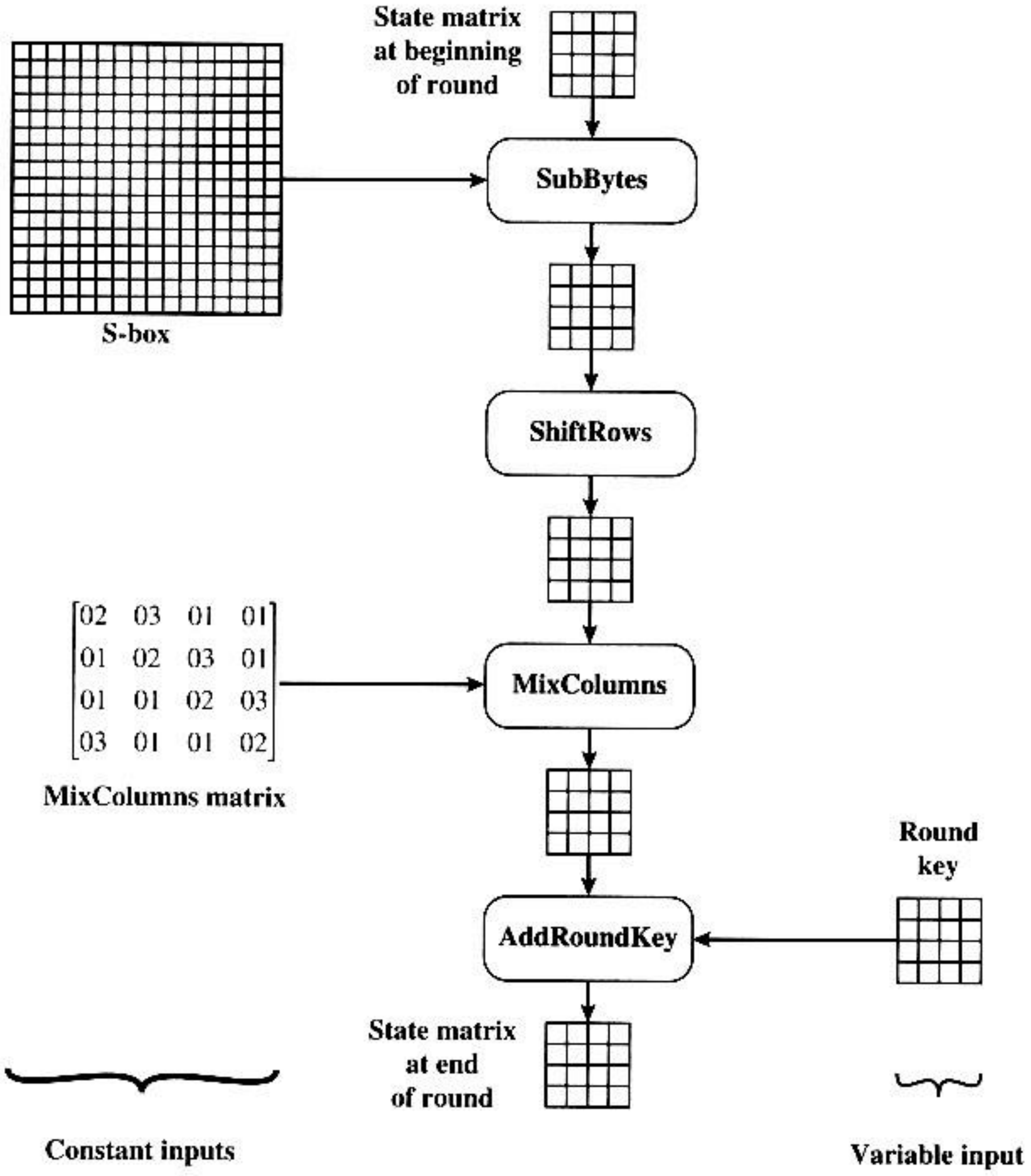
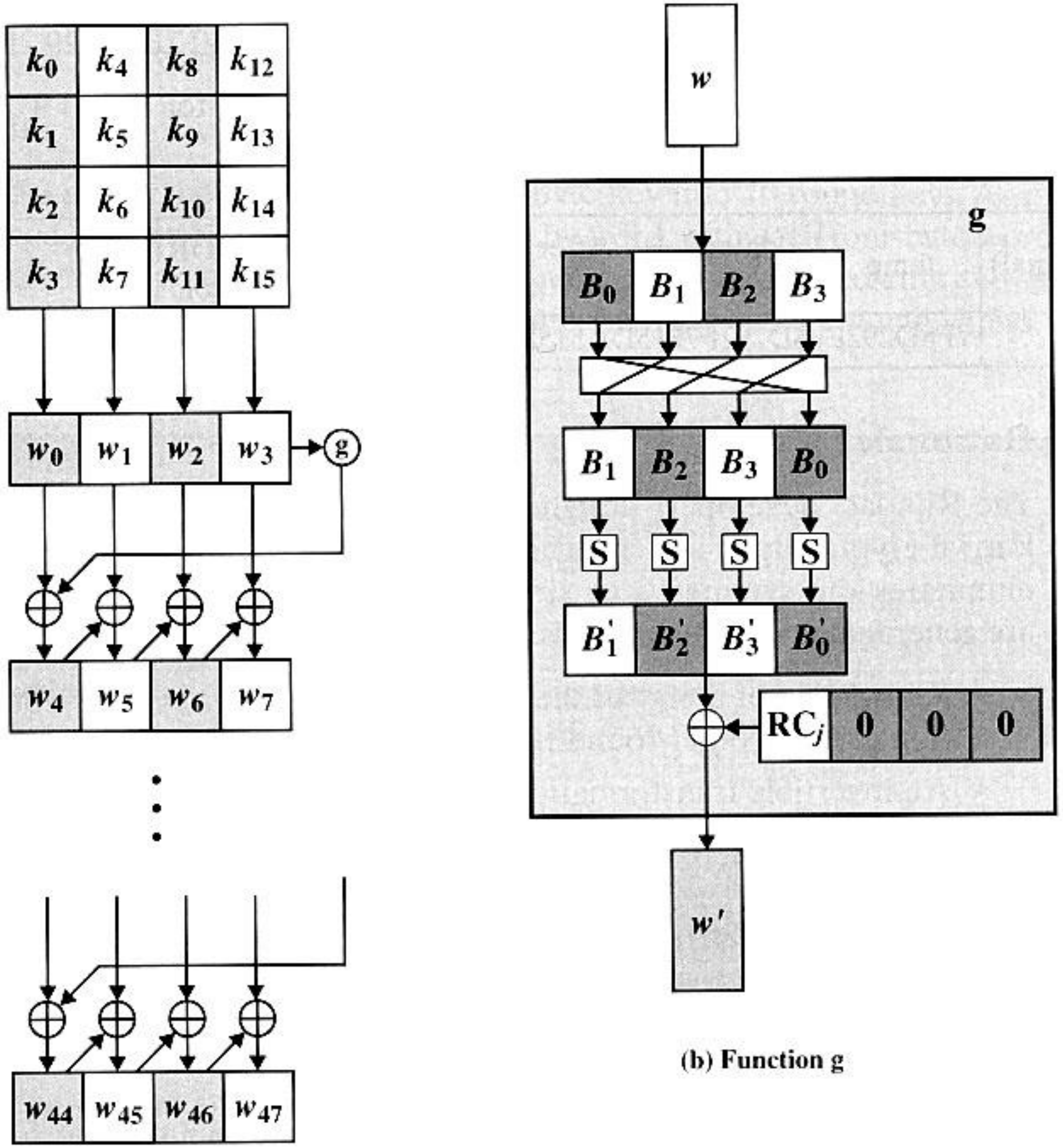


Figure 5.8 Inputs for Single AES Round

readKey and stallingskey.txt

```
void readKey(String filename){
   Scanner in = null;
   try {
     in = new Scanner(new File(filename));
   } catch (FileNotFoundException e){
     System.err.println(filename + " not found");
     System.exit(1);
   }
   hexkey = in.nextLine();
   in.close();
 }
```

```
0f1571c947d9e8590cb7add6af7f6798
```



(b) Function g

(a) Overall algorithm

Figure 5.9 AES Key Expansion

Key Expansion

1. RotWord performs a one-byte circular left shift on a word. This means that an input word $[B_0, B_1, B_2, B_3]$ is transformed into $[B_1, B_2, B_3, B_0]$.
2. SubWord performs a byte substitution on each byte of its input word, using the S-box (Table 5.2a).
3. The result of steps 1 and 2 is XORed with a round constant, Rcon[j].

The round constant is a word in which the three rightmost bytes are always 0. Thus, the effect of an XOR of a word with Rcon is to only perform an XOR on the left-most byte of the word. The round constant is different for each round and is defined as $Rcon[j] = (RC[j], 0, 0, 0)$, with $RC[1] = 1$, $RC[j] = 2 \cdot RC[j-1]$ and with multiplication defined over the field $GF(2^8)$. The values of RC[j] in hexadecimal are

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

expandKey

```
void expandKey(){
   for (int i = 0; i < 16; i++) roundKey[0][i] =
     Integer.parseInt(hexkey.substring(i * 2, (i + 1) * 2), 16);
   int rcon = 1;
   for (int i = 1; i < numberOfRounds; i++){
     roundKey[i][0] = S[roundKey[i-1][13]] ^ rcon;
     rcon <<= 1; if (rcon > 0xFF) rcon ^= 0x11B;
     roundKey[i][1] = S[roundKey[i-1][14]];
     roundKey[i][2] = S[roundKey[i-1][15]];
     roundKey[i][3] = S[roundKey[i-1][12]];
     for (int k = 0; k < 4; k++)
        roundKey[i][k] ^= roundKey[i-1][k];
     for (int k = 4; k < 16; k++)
        roundKey[i][k] = roundKey[i][k-4] ^ roundKey[i-1][k];
   }
}
```

AES Block Cipher

```
void blockCipher(){
   addRoundKey(0);
   for (int i = 1; i < numberOfRounds; i++){
     subBytes();
     shiftRows();
     if (i < numberOfRounds - 1) mixColumns();
     addRoundKey(i);
   }
 }
```

Main and encrypt()

```
void encrypt(){
    while (readBlock() > 0){
      blockCipher();
      writeBlock();
    }
    System.out.flush();
  }
```

```
public static void main(String[] args){
   H11A h11 = new H11A();
   h11.makeLog();
   h11.buildS();
   h11.readKey(args[0]);
   h11.expandKey();
   h11.encrypt();
}
```

Homework 11: due 3-2-15

- Complete the “inverse” versions of the steps in H11B.java so H11B is the inverse of H11A.
- Test your H11B with stallingskey.txt on test11.aes and get the original file to submit along with your code.

```
void decrypt(){
   while (readBlock() > 0){
     blockDecipher();
     writeBlock();
   }
   System.out.flush();
 }


public static void main(String[] args){
   if (args.length < 1){
     System.err.println("Usage: java H11B key < encrypted > original");
     return;
   }
   H11B h11 = new H11B();
   h11.makeLog();
   h11.buildS();
   h11.readKey(args[0]);
   h11.expandKey();
   h11.decrypt();
}
```

blockDecipher and inverseAddRoundKey

```
void inverseAddRoundKey(int round){
   for (int k = 0; k < blockSize; k++)
      state[k] ^= roundKey[?][k];  // which roundkey?
}

void blockDecipher(){
   inverseAddRoundKey(0);
   for (int i = 1; i < numberOfRounds; i++){
      inverseSubBytes();
      inverseShiftRows();
      inverseAddRoundKey(i);
      if (i < numberOfRounds - 1) inverseMixColumns();
   }
}
```

```
void inverseSubBytes(){
   for (int i = 0; i < blockSize; i++)
     state[i] = Si[state[i]];
 }

void inverseShiftRows(){
  // your code here
}

 void inverseMixColumns(){
  int[] temp = new int[4];
  for (int k = 0; k < 4; k++){
   for (int i = 0; i < 4; i++){
     temp[i] = 0;
     for (int j = 0; j < 4; j++)
       temp[i] ^= logMultiply(Gi[j][i], state[k * 4 + j]);
   }
   for (int i = 0; i < 4; i++) state[k * 4 + i] = temp[i];
  }
 }
```

Building Si Table too

```
void buildS(){
     int[] bitColumn = new int[8];
     for (int i = 0; i < fieldSize; i++){
       int inverse = i < 2 ? i : multiplicativeInverse(i);
       for (int k = 0; k < 8; k++)
           bitColumn[k] = inverse >> (7 - k) & 1;
       S[i] = 0;
       for (int k = 0; k < 8; k++){
          int bit = B[k];
          for (int l = 0; l < 8; l++)
            if (bitColumn[l] == 1) bit ^= A[k][l];
          S[i] ^= bit << 7 - k;
       }
       Si[S[i]] = i;
   }
 }
```

Propagation of a Single-Bit Flip (H11C.java)

```
void randomBlock(){
   for (int i = 0; i < blockSize; i++)
      state2[i] = state1[i] = random.nextInt(fieldSize);
   int index = random.nextInt(blockSize);
   state2[index]++;  if (state2[index] >= fieldSize) state2[index] = 0;
 }
```

Blockcipher on Two Blocks

```
void blockCipher(){
   addRoundKey(state1, 0); addRoundKey(state2, 0);
   System.out.print("0 "); numberOfFlips();
   for (int i = 1; i < numberOfRounds; i++){
     subBytes(state1);  subBytes(state2);
     System.out.print(i + " "); numberOfFlips();
     shiftRows(state1); shiftRows(state2);
     System.out.print(i + " "); numberOfFlips();
     if (i < numberOfRounds - 1){ mixColumns(state1); mixColumns(state2); }
     System.out.print(i + " "); numberOfFlips();
     addRoundKey(state1, i);  addRoundKey(state2, i);
   }
 }
```

Comparing Two States

```
void numberOfFlips(){
  int total = 0;
  for (int i = 0; i < blockSize; i++){
    int diff = state1[i] ^ state2[i];
    int nf = 0;
    for (int mask = 0x80; mask > 0; mask >>= 1)
      if ((diff & mask) > 0) nf++;
    total += nf;
    System.out.print(nf + " ");
  }
  System.out.println(total);
}
```

0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	4
1	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	4
1	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	4
1	0	0	0	0	0	0	0	0	4	4	4	4	0	0	0	0	16
2	0	0	0	0	0	0	0	0	5	2	5	6	0	0	0	0	18
2	0	0	5	0	0	2	0	0	5	0	0	0	0	0	0	6	18
2	5	3	4	5	4	2	2	2	4	5	5	3	6	6	3	7	66
3	5	4	4	3	1	4	3	3	5	4	6	2	7	3	2	5	61
3	5	4	6	5	1	4	2	3	5	3	4	3	7	4	3	2	61
3	5	0	5	4	2	4	3	5	7	4	4	4	4	7	4	3	65
4	6	0	3	6	4	1	1	6	2	5	5	6	4	5	4	3	61
4	6	1	5	3	4	5	4	6	2	5	3	6	4	0	1	6	61
4	5	6	1	3	7	5	1	6	2	5	4	5	5	4	4	4	67
5	5	4	5	4	6	5	5	5	5	3	3	3	3	6	6	4	72
5	5	5	3	4	6	3	6	4	5	6	5	5	3	4	5	3	72
5	3	3	2	7	3	4	3	5	3	4	4	2	2	3	4	4	56
6	5	4	4	2	6	1	4	3	5	4	4	7	3	5	4	5	66
6	5	1	4	5	6	4	4	2	5	5	4	3	3	4	4	7	66
6	6	4	5	6	5	4	3	2	3	2	6	4	4	6	4	0	64

7	4	4	2	3	3	3	3	3	4	2	4	4	3	6	3	0	51
7	4	3	4	0	3	2	3	3	4	6	2	3	3	4	3	4	51
7	6	5	2	6	2	3	3	3	5	4	5	3	7	6	4	5	69
8	5	2	2	6	5	4	6	4	7	5	4	5	5	5	3	4	72
8	5	4	4	4	5	5	3	6	7	5	2	4	5	2	6	5	72
8	4	5	3	1	6	4	5	6	4	4	6	4	3	6	3	4	68
9	5	3	5	4	5	5	3	4	3	4	4	3	3	5	4	1	61
9	5	5	4	1	5	4	4	4	3	5	5	4	3	3	3	3	61
9	3	4	5	3	6	6	4	5	4	3	3	5	4	4	3	3	65
10	3	3	5	3	6	4	2	5	4	3	5	5	5	1	2	4	60
10	3	4	5	4	6	3	2	3	4	1	5	5	5	3	2	5	60
10	3	4	5	4	6	3	2	3	4	1	5	5	5	3	2	5	60