Part I

From theory to practice in cryptography

FROM CRYPTO-THEORY to CRYPTO-PRACTICE

In this chapter we deal with several applied cryptography methods, systems and problems that have played very important role in applications.

I. SHIFT REGISTERS

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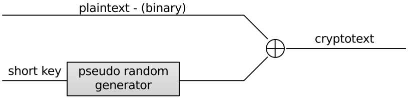

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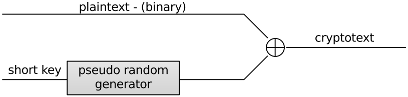
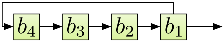
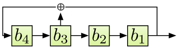


Shift registers as pseudorandom generators

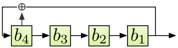


linear shift register



period

0	1	0	0
1	0	1	0
0	1	0	1
0	0	1	0
0	0	0	1
1	0	0	0



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1	1	1	0
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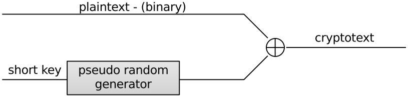

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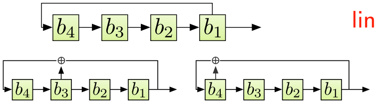

linear shift register

period

b_4	b_3	b_2	b_1
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Theorem For every $n > 0$ there is a linear shift register of maximal period $2^n - 1$.

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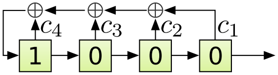

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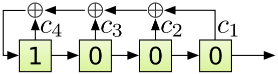

states of cell 4	states of cell 3	states of cell 2	states of cell 1
c_4	1	0	0
$c_4 \oplus c_3$	c_4	1	0
$c_2 \oplus c_4$	$c_4 \oplus c_3$	c_4	1
$c_1 \oplus c_3(c_4 \oplus c_3) \oplus c_4$	$c_2 \oplus c_4$	$c_4 \oplus c_3$	c_4

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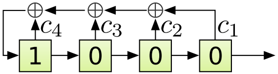

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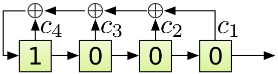
$$\begin{aligned} c_4 &= 1 \\ c_4 \oplus c_3 &= 1 \\ c_2 \oplus c_4 &= 1 \\ c_1 \oplus c_3 \oplus c_4 \oplus c_3 \cdot c_4 &= 0 \end{aligned} \quad \Rightarrow \quad \begin{aligned} c_4 &= 1 \\ c_3 &= 0 \\ c_2 &= 0 \\ c_1 &= 1 \end{aligned}$$

COMPUTATIONS



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After the second step new value of the first register is

$$N = (c_4 \cdot c_4) \oplus c_3 = c_4 \oplus c_3$$

After the third step new value of the first register is

$$N = ((c_4 \oplus c_3) \cdot c_4) \oplus (c_4 \cdot c_3) \oplus c_2$$

If $c_4 = 1$, then

$$N = \bar{c_3} \oplus c_3 \oplus c_2 = \bar{c_2}$$

and therefore $N = c_4 \oplus c_2$.
If $c_4 = 0$, then

$$N = c_2$$

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LINEAR RECURRENCES

Linear feedback shift registers are an efficient way to realize recurrence relations of the type

$$x_{n+m} = c_0 x_n + c_1 x_{n+1} + \cdots + c_{m-1} x_{n+m-1} \text{ (mod n)}$$

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Encryption using one-time pad and a key generated by a linear feedback shift register succumbs easily to a known plaintext attack. As our main example illustrated, if we know few bits of the plaintext and of the corresponding cryptotext, one can easily determine the initial part of the key and then the corresponding linear recurrence, as already shown.

FINDING LINEAR RECURRENCES - A METHOD - I.

To test whether a given portion of a bit sequence was generated by a recurrence of a length m, if we know the sequence prefix $x_1, \ldots, x_{2m}$, we need to solve the matrix equation

$$\begin{pmatrix} x_1 & x_2 & \ldots & x_m \\ x_2 & x_3 & \ldots & x_{m+1} \\ \vdots & \vdots & \ddots & \vdots \\ x_m & x_{m+1} & \ldots & x_{2m-1} \end{pmatrix} \begin{pmatrix} c_0 \\ c_1 \\ \vdots \\ c_{m-1} \end{pmatrix} = \begin{pmatrix} x_{m+1} \\ x_{m+2} \\ \vdots \\ x_{2m} \end{pmatrix}$$

and then to verify whether the remaining available bits of the sequence, $x_{2m+1}, \ldots$, are really generated by the recurrence just obtained.

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be a plaintext.
Define, for $0 \leq i < s$, $p_{-i} = k_{s-i}$, and construct the cryptotext by

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Example: polyalphabetic substitutions.

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IV. DES CRYPTOSYSTEM and its FOLLOWERS

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After 3 years of arguing of experts, a 56-bit key version of Lucifer was accepted (supposedly only for the next 5 years) as the standard called DES (Data Encryption Standard) on November 23, 1976.

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1. Both encryption and decryption algorithms were made public!!!!!!

The same algorithms, software systems or hardware could be used for both encyption and decryption.

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$$L_i = R_{i-1}$$
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where f is a fixed+public and easy-to-implement function.
The cryptotext $c = \phi_{64}^{-1}(L_{16}, R_{16})$

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Decryption $\phi_{64}(c) = L_{16}R_{16}$ is computed and then the recurrence

$$R_{i-1} = L_i$$
$$L_{i-1} = R_i \oplus f(L_i, K_i),$$

is used to get L_i, R_i i = 15,...,1,0, w = $\phi_{64}^{-1}(L_0, R_0)$.

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56 bits of the key are now subject to the following fixed+public permutation ϕ_{56}:

57	49	41	33	25	17	9
1	58	50	42	34	26	18
10	2	59	51	43	35	27
19	11	3	60	52	44	36
63	55	47	39	31	23	15
7	62	54	46	38	30	22
14	6	61	53	45	37	29
21	13	5	28	20	12	4

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Blocks C_i, D_i for $i = 1, 2, \ldots, 16$ are now constructed from blocks C_{i-1}, D_{i-1} by one or two left shifts according the following table

ble:

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	1	2	2	2	2	2	2	1	2	2	2	2	2	2	1

shift means a rotation of the bits one place to the left; after one left

NEXT STEP II

Using a fixed and publicly known order,

14	17	11	24	1	5
3	28	15	6	21	10
23	19	12	4	26	8
16	7	27	20	13	2
41	52	31	37	47	55
30	40	51	45	33	48
44	49	39	56	34	53
46	42	50	36	29	32

16 subkeys k_i, each of 48 bits, are then created, each k_i from blocks C_i, D_i

DES -ENCRYPTION DETAILS

A fixed+public initial permutation ϕ_{64}

58	50	42	34	26	18	10	2
60	52	44	36	28	20	12	4
62	54	46	38	30	22	14	6
64	56	48	40	32	24	16	8
57	49	41	33	25	17	9	1
59	51	43	35	27	19	11	3
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At first, the 32-bit block is expanded into 48-bits according the following table:

32	1	2	3	4	5
4	5	6	7	8	9
8	9	10	11	12	13
12	13	14	15	16	17
16	17	18	19	20	21
20	21	22	23	24	25
24	25	26	27	28	29
28	29	30	31	32	1

After this expansion two 48-bits blocks are XOR-ed - bit by bit.

DES - ENCRYPTION - CONTINUATION

The resulting block of 48 bits is now divided into eight 6-bit blocks $B_1, B_2, \ldots, B_8$ and j-th of these eight 6-bit blocks is transformed into a 4-bit block using table S_j. The first two of them are:

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4	1	14	8	13	6	2	11	15	12	9	7	3	10	5	0
15	12	8	2	4	9	1	7	5	11	3	14	10	0	6	13

S_2

15	1	8	14	6	11	3	4	9	7	2	13	12	0	5	10
3	13	4	7	15	2	8	14	12	0	1	10	6	9	11	5
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15	12	8	2	4	9	1	7	5	11	3	14	10	0	6	13

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Transformation is performed as follows. For a given 8-bit string, the first and last bit determine a number $x \in \{0, 1, 2, 3\}$ and the middle four bits a number y. The number in x-row and y-column is then written in binary.

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Example: for the string 110010, we have $x = 2$, $y = 9$ and the resulting number defined by S_1 is 15. Therefore the resulting string is 1111.

KEY ELEMENTS of DES

- A cryptosystem is called linear if each bit of cryptotext is a linear combination of bits of plaintext.
- For linear cryptosystems there is a powerful decryption method - so-called linear cryptanalysis.
- The only components of DES that are non-linear are S-boxes.
- Some of original requirements for S-boxes:
  - Each row of an S-box should include all possible output bit combinations;
  - It two inputs to an S-box differ in precisely one bit, then the output must differ in a minimum of two bits;
  - If two inputs to an S-box differ in their first two bits, but have identical last two bits, the two outputs have to be distinct.
- There have been many other very technical requirements.

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How to increase security when encrypting long plaintexts?

$$w = m_1 m_2 \dots m_n$$

where each m_i has 64-bits.
Choose a 56-bit key k and a 64-bit block c_0 and compute

$$c_i = DES(m_i \oplus c_{i-1})$$

for i = 1,...,n.

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Brute force: $2^{56} \times 2^{56} = 2^{2\times 56} = 2^{112}$;

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MITM attack has been generalized for the case on n-multiple encodings are used for DES and some other cryptosystems.

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4. In 1993 M. Wiener suggested a machine of the cost \$ 100.000 that could find the key in 1.5 days.

WEAKNESSES of DES

- Existence of weak keys: they are such keys k that for any plaintext p,

$$E_k(E_k(p)) = p.$$

There are four such keys:
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- The existence of complementation property
$$E_{c(k)}(c(p)) = c(E_k(p)),$$
where c(x) is binary complement of binary string x.

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This mode is very fast because a key stream can be parallelised to any degree. Because of that this mode is used in network security applications.

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- In 1999 they did that in 24 hours.
- It started to be clear that a new cryptosystem with larger keys is badly needed.

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For $0 < I < r + 1$, the round i maps (L_{i-1}, R_{i-1}) to (L_i, R_i) using a subkey K_i as follows

$$L_i = R_{i-1},\ R_i = K_{i-1} \oplus f(R_{i-1}, K_i),$$

where each subkey K_i is derived from the main key K.

BLOWFISH CRYPTOSYSTEM

- Blowfish is a Feistel type cryptosystem developed in 1993 by Bruce Schneier.
- **Blowfish is more secure and faster than DES.**
- It encrypts 8-bytes blocks into 8-bytes blocks.
- **Key length is a variable 32k, for k = 1, 2, . . . , 14.**
- For decryption, Blowfish does not reverse the order of encryption, but follows it.
- **S-boxes are of key dependence and they, as well as subkeys, are created by repeated execution of Blowfish enciphering transformation.**
- Blowfish has very strong avalanche effect.
- **A follower of Blowfish, Twofish, was one of 5 main candidates for AES.**
- Blowfish can be downloaded free from the B. Schneier web site.

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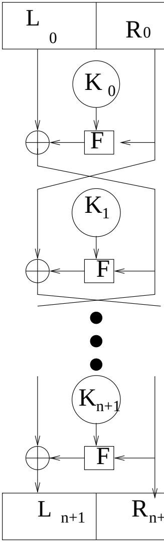
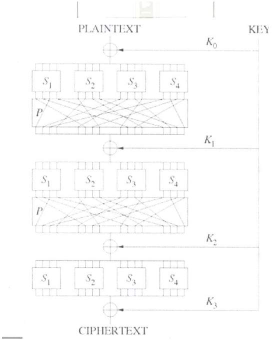


SUBSTITUTION-PERMUTATION ENCRYPTION/DECRYPTION SCHEMES

This scheme, known also as **substitution-permutation network**, is an encryption/decryption method/network that performs a series of substitution-permutation layers of operations composed of S-boxes (substitution boxes) and P-boxes (permutation boxes) as shown in the picture - K_i are keys.



Encryption/decryption system AES discussed next is the most known example of such a system.

V. AES CRYPTOSYSTEM

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- High security as well as fast speed and low memory requirements on a variety of computing systems were main criteria.

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Motivations and advantages of AES:

- Short code and fast and low memory implementations.
- Simplicity and transparency of the design.
- Variable key length.
- Resistance against all known attacks.

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OPERATIONS in THE FIELD $GF(2^8)$

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Addition

In polynomial representation, the sum of two bytes is the polynomial whose coeficiants are given by xor-ing coefficients of both bytes-polynomials.

$$(x^6 + x^4 + x^2 + x + 1) + (x^7 + x + 1) = x^7 + x^6 + x_4 + x^2$$

Multiplication

In polynomial representation of bytes, multiplication in $GF(2^8)$ corresponds with multiplication of polynomials modulo an irreducible polynomial

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

Example

$$(x^6 + x^4 + x^2 + x + 1)(x^7 + x + 1) = x^{13} + x^{11} + x^9 + x^8 + x^5 + x^5 + x^4 + x^3 + 1$$

and

$$(x^{13} + x^{11} + x^9 + x^8 + x^5 + x^5 + x^4 + x^3 + 1) \bmod m(x) = x^7 + x_6 + 1$$

The set of 256 possible byte values with operations of addition and multiplication as defined above has the structure of the finite field $GF(2^8)$.

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In polynomial representation **multiplication** of two polynomilas is done performing usual multiplicaion and then taking modulus a special polynomial in such a way that multiplication has inverse elements.

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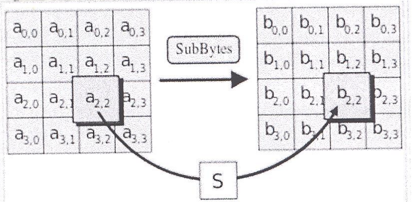
  4. **AddRoundKey** - bit-wise XOR with a round key defined by another matrix.

THE SubBytes STEP



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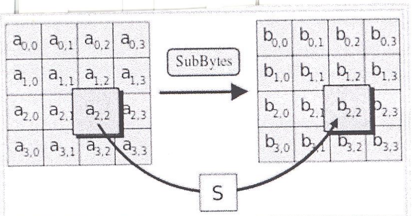

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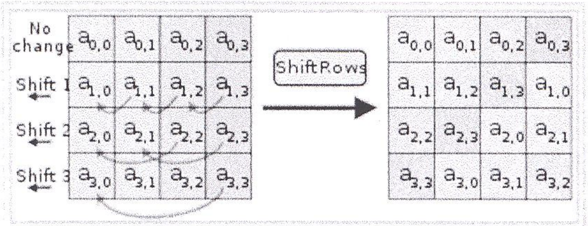
- In this step, each byte in the state is replaced with its entry in a fixed 8-bit lookup table.
- The operation introduces non-linearity into encryption.
- At decryption, an **Inverse SubBytes** step is used.

THE ShiftRows STEP



In the `ShiftRows` step, bytes in each row of the state are shifted cyclically to the left. The number of places each byte is shifted differs for each row.

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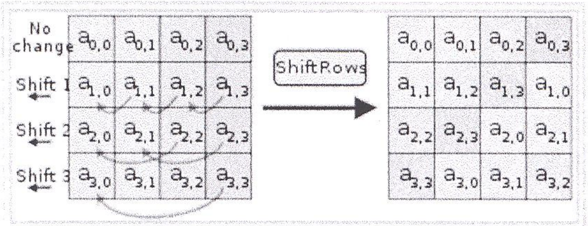
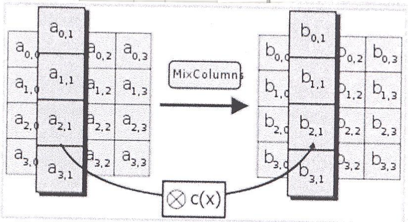


In the ShiftRows step, bytes in each row of the state are shifted cyclically to the left. The number of places each byte is shifted differs for each row.

- At this step each row of the state is cyclically shifted by a certain offset.
- This step is done to avoid that columns of states are linearly dependent.

THE MixColumns STEP



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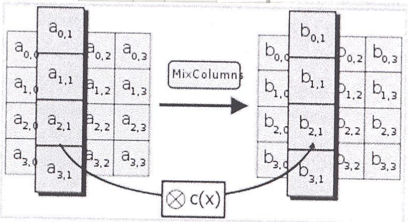
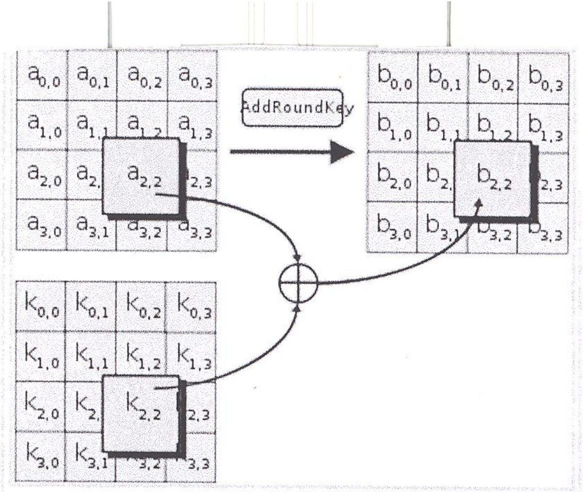


In the `MixColumns` step, each column of the state is multiplied with a fixed polynomial $c(x)$.

During this step, each column is multiplied by the matrix

$$\begin{bmatrix} 2 & 3 & 1 & 1 \\ 1 & 2 & 3 & 1 \\ 1 & 1 & 2 & 3 \\ 3 & 1 & 1 & 2 \end{bmatrix}$$

THE AddRoundKey STEP



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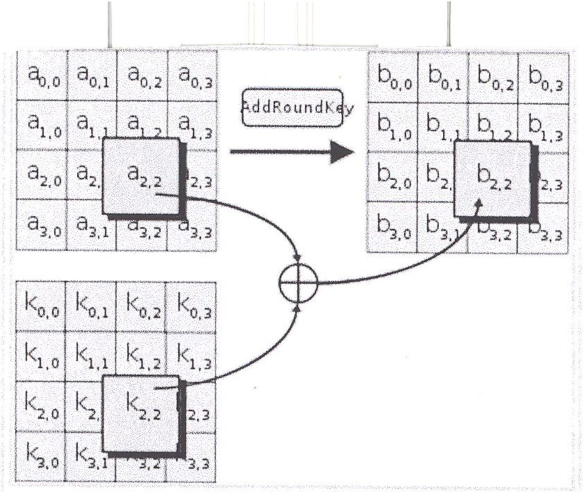

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On Intel Core i3/i5/i7 CPUs supporting AES-NI instruction set extensions, throughput can be over 700 MB/s.

BYTE-WISE SUBSTITUTION

Byte-wise substitution $\mathrm{b} = \mathrm{SubByte(a)}$ is defined by the following matrix operations

$$\begin{pmatrix} b_7 \\ b_6 \\ b_5 \\ b_4 \\ b_3 \\ b_2 \\ b_1 \\ b_0 \end{pmatrix} = \begin{pmatrix} 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 & 1 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \\ 1 & 1 & 0 & 0 & 0 & 1 & 1 & 1 \\ 1 & 1 & 1 & 0 & 0 & 0 & 1 & 1 \\ 1 & 1 & 1 & 1 & 0 & 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} (a^{-1})_7 \\ (a^{-1})_6 \\ (a^{-1})_5 \\ (a^{-1})_4 \\ (a^{-1})_3 \\ (a^{-1})_2 \\ (a^{-1})_1 \\ (a^{-1})_0 \end{pmatrix} + \begin{pmatrix} 0 \\ 1 \\ 1 \\ 0 \\ 0 \\ 0 \\ 1 \\ 1 \end{pmatrix}$$

This operation is computationally heavy and it is assumed that it will be implemented by a pre-computed substitution table.

ENCRYPTION in AES

Encryption and decryption are done using state matrices

A	E	I	M
B	F	J	N
C	G	K	O
D	H	L	P

elements of which are bytes.

A byte-matrix with 4 rows and k = 4, 6 or 8 columns is also used to write down a key with D_k = 128, 192 or 256 bits.

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The final round does not contain MixColumn procedure. The reason being is to be able to use the same hardware for encryption and decryption.

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The key extension algorithm generates new columns W_i of the state matrix from the columns W_{i-1} and W_{i-k} using the following rule

$$W_i = W_{i-k} \oplus V,$$

where

$$\mathrm{V} = \begin{cases} F(W_{i-1}), & \text{if i mod k} = 0 \\ G(W_{i-1}), & \text{if i mod k} = 4 \text{ and } D_k = 256 \text{ bits,} \\ W_{i-1} & \text{otherwise} \end{cases}$$

and where the function G performs only the byte-substitution of the corresponding bytes. **F**unction F is defined in a quite a complicated way.

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SECURITY GOALS

The goal of the authors was that Rijndael (AES) is K-secure and hermetic in the following sense:

Definition A cryptosystem is K-secure if all possible attack strategies for it have the same expected work factor and storage requirements as for the majority of possible cryptosystems with the same security.

Definition A block cryptosystem is hermetic if it does not have weaknesses that are not present for the majority of cryptosystems with the same block and key length.

MISCELLANEOUS

Pronunciation of the name **Rijndael** is as “Reign Dahl’‘ or “rain Doll” or “Rhine Dahl”.

AES attacks

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Complexity of the biclique attack

- AES-128 - $2^{126.1}$ - brute force (2^{128}).
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Comment 1: Biclique is a complete bipartite graph - all nodes of which are connected to all potential neighbours.

Comment 2: For cryptographers, a cryptographic "break" is anything faster than a brute force.

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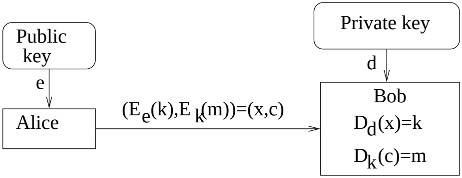

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VIII. CRYPTANALYSIS

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Security is measured in such cases in terms of such encryption parameters as the length of the key and the size of message space.

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A generalization for searching for several keys having several values $C_k(x)$ is easy.

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Linear analysis: This is a dual method to differential cryptanalysis invented after discovering anomalies in S-boxes in DES. The idea is not to keep track of difference propagation by the chosen plaintext attack, but to keep track of Boolean information which is linearly obtained by a known plaintext attack: if one gets $(x, c(x))$ pair a statistical analysis of the special Boolean information $L(x, c(x))$ is made and some information on the key is deduced.

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For AES-128 (AES-192) [AES-256] the key can be recovered with a computational complexity $2^{126.1}$ ($2^{189.7}$) [$2^{254.4}$].

APPENDIX