

# A history of the application of MDS matrices in cryptography

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# Contents

<b>1</b>	<b>A history of the application of MDS matrices in cryptography</b>	<b>2</b>
1.1	Notation . . . . .	3
1.2	Acronyms . . . . .	4
1.3	Preliminaries . . . . .	4
1.3.1	Linear codes . . . . .	4
1.3.2	Matrices . . . . .	5
1.3.3	Evaluating a matrix for MDS property . . . . .	8
1.3.4	Abstract algebra . . . . .	9
1.3.5	Finite fields — $\text{GF}(2^m)$ . . . . .	9
1.3.6	Computational cost unit . . . . .	10
1.4	MDS matrix catalogue . . . . .	11
1.5	A note on Hierocrypt 3 and Hierocrypt-L1 . . . . .	17
1.6	A note on Whirlpool-0 . . . . .	18
1.7	Non-MDS matrix catalogue . . . . .	20
1.8	About the irreducible polynomials . . . . .	20
1.9	Computing <b>xtime</b> and <b>xor</b> of the matrices . . . . .	21
1.9.1	SQUARE manual calculation example . . . . .	22
1.10	Conclusions . . . . .	23

# Chapter 1

## A history of the application of MDS matrices in cryptography

MDS matrices have been widely used in the construction of diffusion layers for block ciphers such as SHARK [23], SQUARE [11], BKSQ [12], KHAZAD [3], ANUBIS [2], Hierocrypt-3 [9], Rijndael (AES) [13] and Curupira [4]. They have also been applied in the design of hash functions (e.g Whirlwind [1] and Grøstl [14]). The choice is due to the fact that MDS codes provide transformations with optimal linear and differential branch numbers (see e.g [11] or [23]), thus contributing to security against Differential and Linear Cryptanalysis attacks.

When a matrix is MDS, optimal *branch number* (a measure of diffusion power) is ensured, therefore, from the theoretical security perspective, any two distinct  $n \times n$  MDS matrices present equal contribution to a cipher's design in terms of diffusion power. However, their computational cost, which is a relevant practical implementation criterion, *is not* necessarily the same. This motivates not only the search for MDS matrices, but the search for *MDS matrices with low computational cost*. In this work, the computational cost of a matrix  $A$  is measured by the amount of **xor** and **xtime** operations required when multiplying a cipher's state column vector by  $A$ .

Due to the computational cost of matrix multiplication, there is an interest in finding MDS matrices with coefficients as small as possible, in order to minimize the required amount of **xor** and **xtime** operations required by the implementations. However, the complexity of finding MDS matrices through random search increases proportionally to the dimension, which led to the investigation of systematic methods to construct (or find) MDS matrices. One possible avenue is trying to find direct mathematical constructions which ensure the MDS property, and another is to impose restrictions to limit the random search space (e.g imposing the matrix should be circulant, as was done by the authors of [11]). Furthermore, there is an interest in finding involutory MDS

matrices (as pointed by [3] and [2]), so that the encryption and the decryption computational cost are the same.

It is also worth noting that, although MDS matrices are widely used in cryptographic algorithms, there are designs which prefer not to make use of them. The block ciphers Serpent [7], IDEA [17] and PRESENT [8], for instance, do not include MDS matrices in their design. The hash function Keccak [6], which was later selected by NIST to become the SHA-3 standard, also does not use MDS matrices. The computational cost can be related to this choice.

In this chapter, we aim at providing a history of the application of MDS matrices in cryptography, listing the matrices, the ciphers in which they have been applied, the respective Finite Fields (order and irreducible polynomial), and their cost (amount of **xor** and **xtime** operations).

**Note: this is a partial report. It will be expanded in the future.**

We assume the reader is familiar with:

- Linear branch number (see **Chapter X**)
- Differential branch number (see **Chapter X**)
- Differential Cryptanalysis (see **Chapter X**)
- Linear Cryptanalysis (see **Chapter X**)
- MDS codes (see **Chapter X** and, for further detail, reference [19])
- Diffusion property in cryptography (see **Chapter X**)
- Groups, rings and fields in abstract algebra (see **Chapter X**)

## 1.1 Notation

- $\det(A)$ : determinant of the matrix  $A$
- $A^{-1}$ : inverse matrix of  $A$
- $n, k, d$ : parameters of a code
- $\mathcal{C}$ : a code
- $G$ : generator matrix of a code
- $I_n$ : the  $n \times n$  identity matrix
- $[I_n B]$ : matrix obtained by placing the  $n \times n$  matrix  $B$  to the right of the  $n \times n$  identity matrix  $I_n$ . For example, for  $B = \begin{bmatrix} 1 & 2 \\ 3 & 4 \end{bmatrix}$ ,  $[I_n B] = \begin{bmatrix} 1 & 0 & 1 & 2 \\ 0 & 1 & 3 & 4 \end{bmatrix}$

## 1.2 Acronyms

- **MDS**: Maximum Distance Separable
- **AES**: Advanced Encryption Standard (Rijndael's name after being chosen by NIST)
- **xor**: bitwise XOR between two bit strings
- **xtime**: refers to the multiplication by the polynomial  $x$  in the finite field  $\text{GF}(2^m)$  for an integer  $m$

## 1.3 Preliminaries

### 1.3.1 Linear codes

**Definition 1 (Hamming weight [19])** *The Hamming weight  $w(x)$  of a vector  $x$  is the number of nonzero components of the vector  $x$ .*

**Definition 2 (Hamming distance [19])** *The Hamming distance between two vectors  $x$  and  $y$  is  $w(x - y)$ , which is equal to the Hamming weight of the difference of the two vectors.*

**Definition 3 (Linear code [19])** *A linear  $[n, k, d]$  code over a field  $\mathbb{F}$  is a  $k$ -dimensional subspace of the vector space  $\mathbb{F}^n$ , where any two different vectors of the subspace have a Hamming distance of at least  $d$ , and  $d$  is the largest number with this property.*

*The distance  $d$  of a linear code equals the minimum weight of a non-zero codeword in the code. A linear code can be described by generator and/or parity-check matrices.*

**Definition 4 (Generator matrix [19])** *A generator matrix  $G$  for an  $[n, k, d]$  code  $C$  is a  $k \times n$  matrix whose rows form a vector space basis for  $C$ . The choice of a basis in a vector space is not unique, thus a code has many different generator matrices which can be reduced to one another by performing elementary row operations.*

**Definition 5 (Parity-check matrix [19])** *A parity-check matrix  $H$  for an  $[n, k, d]$  code  $C$  is an  $(n - k) \times k$  matrix with the property that a vector  $x$  is a codeword of  $C$  iff  $Hx^T = 0$ .*

**Theorem 1 (Singleton Bound [19])** *If  $C$  is an  $[n, k, d]$  code, then  $d \leq n - k + 1$ .*

**Definition 6 (MDS code [19])** *An MDS code is a linear code that meets the Singleton bound, i.e. a linear code with  $d = n - k + 1$ .*

An MDS matrix associated to a  $[n, k, d]$  code has *branch number* equal to  $d$ , which is the maximum possible branch number, thus providing optimal diffusion.

**Definition 7 (Branch number [24])** The branch number  $\mathcal{B}$  of a linear mapping  $\theta : GF(2^m)^k \rightarrow GF(2^m)^l$  is defined as:

$$\mathcal{B}(\theta) = \min_{a \neq 0} \{w(a) + w(\theta(a))\}.$$

Note that here,  $+$  denotes a XOR operation, since the fields have characteristic equal to 2.

Furthermore, given a matrix  $M$ , associated to a  $[n, k, d]$  linear code, the linear mapping defined by  $\theta(a) = a \cdot M$  has branch number  $\mathcal{B}(\theta) = d$ . When the linear code is MDS, i.e when  $M$  is MDS, the mapping is an optimal diffusion mapping.

### 1.3.2 Matrices

Obs: eu escrevi essas primeiras definições (matriz singular, involutória, circulante, circulante à esquerda, circulante à direita) com base no que eu lembrava de matemática mesmo, então por hora ainda não coloquei uma referência bibliográfica, já que são definições mais gerais e não chegam a ser específicas de cripto. Mas posso colocar depois se necessário.

**Definition 8 (Singular matrix)** A square matrix  $A$  is singular if and only if  $\det(A) = 0$ .

**Definition 9 (Non-singular matrix)**  $A$  is non-singular if and only if  $\det(A) \neq 0$ .

**Definition 10 (Involutory matrix)** An  $n \times n$  square matrix  $A$  is involutory if  $A \times A = I_n$ , where  $I_n$  is the identity matrix. In other words,  $A$  is involutory when  $A = A^{-1}$ .

**Definition 11 (Circulant matrix)** An  $n \times n$  matrix  $A$  is circulant if each row  $i$  is formed by a cyclical shift of  $i$  positions of the same set of elements  $\{a_0, a_1, a_2, \dots, a_{n-1}\}$ .

**Definition 12 (Left circulant matrix)** A circulant matrix in which the shift is a cyclical shift to the left, i.e

$$A = \begin{bmatrix} a_0 & a_1 & \dots & \dots & a_{n-1} \\ a_1 & a_2 & \dots & a_{n-1} & a_0 \\ \dots & \dots & \dots & \dots & \dots \\ a_{n-1} & a_0 & \dots & \dots & a_{n-2} \end{bmatrix}.$$

**Definition 13 (Right circulant matrix)** A circulant matrix in which the shift is a cyclical shift to the right, i.e

$$A = \begin{bmatrix} a_0 & a_1 & \dots & \dots & a_{n-1} \\ a_{n-1} & a_0 & a_1 & \dots & a_{n-2} \\ \dots & \dots & \dots & \dots & \dots \\ a_1 & \dots & a_{n-2} & a_{n-1} & a_0 \end{bmatrix}.$$

Note that circulant matrices can be defined by just one row, since all the other rows are cyclical shifts of the first. Therefore, they can be denoted as  $\text{circ}(a_0, a_1, \dots, a_{n-1})$ . In the case of left circulant and right circulant matrices, respectively,  $\text{lcirc}(a_0, \dots, a_{n-1})$  and  $\text{rcirc}(a_0, \dots, a_{n-1})$ . For example, matrices (1.11) and its inverse (1.11), used in the Rijndael cipher, can be denoted as  $\text{rcirc}(02_x, 03_x, 01_x, 01_x)$  and  $\text{rcirc}(0e_x, 0b_x, 0d_x, 09_x)$ . Since a circulant matrix can be defined by one row only, only  $n$  elements are required, and this optimizes the process of searching for (and finding) such matrices. However, *there are no guarantees about the MDS property*. One must check whether Theorem 2 holds to ensure the obtained matrix is MDS. As an example, the circulant matrix initially employed in Whirlpool-0 [25] is not MDS, and was further replaced by an actual MDS matrix found by Shirai in [24].

**Definition 14 (Transpose matrix)** *The transpose of a matrix  $A$ , denoted by  $A^T$ , is the matrix such that  $A^T[i][j] = A[j][i]$ . In other words, it is the matrix obtained by writing the rows of  $A$  as columns. Note that, if  $A$  is an  $m \times n$  matrix, then  $A^T$  will be  $n \times m$ .*

**Definition 15 (Submatrix)** *Given a matrix  $M$ , a submatrix of  $M$  is the matrix obtained after removing  $z$  rows and columns of  $M$ ,  $z \geq 1$ , provided that there are sufficient rows (and columns) to be removed.*

**Theorem 2 (MDS codes [19])** *An  $[n, k, d]$ -code  $\mathcal{C}$  with generator matrix  $G = [I_n B]$ , where  $B$  is a  $k \times (n - k)$  matrix, is MDS if and only if every square submatrix of  $B$  is non-singular.*

We call the  $B$  matrix of Theorem 2 the *MDS matrix* throughout this work, i.e the MDS matrices we study are the  $B$  matrices of the respective MDS codes chosen when designing them. Note that Definition 6 establishes the conditions for a code to be MDS, therefore Theorem 2 is an alternative way of evaluating a code, or a matrix, with respect to the MDS property. For further detail on matrices, determinants and linear algebra, the reader may refer to [18].

**Definition 16 (Cauchy matrix)** *Given  $x_0, \dots, x_{n-1}$  and  $y_0, \dots, y_{n-1}$ , the matrix  $A$  where  $A[i][j] = \frac{1}{x_i + y_j}$  is called a Cauchy matrix. According to [26], provided that  $x_i \neq x_j$  for  $0 \leq i, j \leq n - 1$ , that  $y_i \neq y_j$  for  $0 \leq i, j \leq n - 1$  and that  $x_i + y_j \neq 0$  for all  $i, j$ , any square submatrix of a Cauchy matrix is nonsingular over any field.*

It is worth noting that a Cauchy matrix construction directly ensures the MDS property, as can be seen in Definition 16, and it requires only  $2n$  choices of elements, since the  $x_i$  and the  $y_i$  must be defined.

**Definition 17 (Hadamard matrix [5])** *Given  $n$  elements  $a_0, a_1, \dots, a_{n-1}$ ,  $n$  being a power of 2, the matrix  $H$  such that  $H[i][j] = a_{i \oplus j}$  is a Hadamard matrix.*

In Whirlwind[1], the authors make use of *dyadic* matrices, defining them as a matrix  $S$  such that  $S[i][j] = s_{i \oplus j}$  given a set  $s_0, s_1, \dots, s_{n-1}$  of  $n$  elements.

This definition matches Definition 17, which is used in Anubis and Khazad, but referred as Hadamard instead of dyadic. Therefore, for dyadic matrices, the same situation described for Hadamard applies: a dyadic construction allows us to reduce the scope of the element choice, i.e only  $n$  elements must be chosen, but there is no guarantee of MDS property.

Note that a Hadamard construction, similarly to a circulant construction, requires only  $n$  elements to be defined, but it does not guarantee MDS property either. To the best of our knowledge, no proofs about Hadamard matrices being MDS have been presented in the literature at the time of writing. Furthermore, in this work, we believe we present an example of a Hadamard non-MDS matrix. See Section 1.7 for further detail on this.

**Definition 18 (Vandermonde matrix [15])** *Given  $z$  elements  $a_0, a_1, \dots, a_{z-1}$ , the  $z \times n$  matrix  $V$  such that*

$$V = \begin{bmatrix} 1 & a_0 & a_0^2 & \dots & a_0^{n-1} \\ 1 & a_1 & a_1^2 & \dots & a_1^{n-1} \\ \dots & \dots & \dots & \dots & \dots \\ 1 & a_{z-1} & a_{z-1}^2 & \dots & a_{z-1}^{n-1} \end{bmatrix} \quad (1.1)$$

*is a Vandermonde matrix.*

Similarly to circulant and Hadamard constructions, in the case of the Vandermonde matrix,  $z$  elements are required and then we must choose the number of columns  $n$ . Not all Vandermonde matrices are square matrices, but the notion of MDS matrix applies only to square matrices. Therefore,  $z$  must be equal to  $n$  if we wish to construct a Vandermonde MDS matrix. However, again there are no guarantees about the MDS property with a Vandermonde construction. To the best of our knowledge, at the time of writing, there are no such guarantees. The matrices must be constructed and then evaluated with respect to the MDS property, e.g using Theorem 2.

## A summary on the types of matrices

An  $n \times n$  matrix possesses  $n^2$  elements and thus, when constructing one e.g by selecting random elements,  $n^2$  choices must be made. However, Cauchy, circulant, Vandermonde and Hadamard (dyadic) constructions allow us to lower the number of elements we need to select. Circulant, Vandermonde and Hadamard constructions allow us to select only  $n$  elements, whilst Cauchy constructions require selecting  $2n$  elements. The Cauchy construction ensures MDS property, whilst the other constructions do not and e.g Theorem 2 must be used to evaluate MDS property. Furthermore, it is relevant to note that, albeit most matrices in this work have their dimension  $n$  be a power of two such as 4 or 8, this is not a requirement for the construction. One can construct  $n \times n$  circulant (or Cauchy, or Vandermonde) matrices for any arbitrary  $n$ . The dimension  $n$  must only be a power of two for the Hadamard (dyadic) construction. Table 1.1 summarizes this information.



Type	Elements to select	MDS guarantee	$n$ must be power of two
Circulant	$n$	no	no
Hadamard (dyadic)	$n$	no	yes
Vandermonde	$n$	no	no
Cauchy	$2n$	yes	no
random	$n^2$	no	no

Table 1.1: Matrix classification summary

### 1.3.3 Evaluating a matrix for MDS property

If Theorem 2 is used, the determinant of the matrix itself must be calculated, as well as the determinants of its submatrices. First, we derive a formula for the cost of calculating the determinant of an  $n \times n$  matrix. Our cost unit is *the number of multiplications in a finite field*, since it is the most expensive operation.

The determinant of a  $2 \times 2$  matrix  $\begin{bmatrix} a & b \\ c & d \end{bmatrix}$  can be computed by means of the formula  $ad - bc$ , requiring therefore two multiplications.

The determinant of a  $3 \times 3$  matrix can be computed by calculating cofactors of  $2 \times 2$  submatrices obtained by removing a row  $i$  and a column  $j$ . For example,

the determinant of  $\begin{bmatrix} a & b & c \\ d & e & f \\ g & h & i \end{bmatrix}$  can be computed as  $a \begin{vmatrix} e & f \\ h & i \end{vmatrix} + b \begin{vmatrix} d & f \\ g & i \end{vmatrix} + c \begin{vmatrix} d & e \\ g & h \end{vmatrix}$ ,

where  $\begin{vmatrix} e & f \\ h & i \end{vmatrix}$  denotes the determinant of the submatrix  $\begin{bmatrix} e & f \\ h & i \end{bmatrix}$ .

The cost is therefore  $3 + 3t(2)$ , where  $t(2)$  is the number of multiplications required to compute the determinant of a  $2 \times 2$  matrix. We know that  $t(2) = 2$ , therefore the cost to obtain the determinant of a  $3 \times 3$  matrix is  $3 + 3 \times 2 = 9$ , i.e  $t(3) = 9$ . Extending this logic, let  $t(n)$  be the cost of obtaining the determinant of an  $n \times n$  matrix. Then  $t(n) = n + nt(n-1) = n + n(n-1 + (n-1)t(n-2)) = n + n(n-1) + n(n-1)t(n-2) = n + n(n-1) + n(n-1)(n-2) + \dots + n(n-1)(n-2) \dots 2$ . For example, for  $n = 4$ ,  $t(4) = 4 + 4 \times 3 + 4 \times 3 \times 2 = 4 + 12 + 24 = 40$  multiplications in a finite field.

In order to evaluate a matrix for MDS property, we must compute the determinants of all its square submatrices. Let  $A$  be an  $n \times n$  matrix. A submatrix of  $A$  is obtained by removing  $z$  rows and columns of  $A$ . The possible values of  $z$  range from 1 to  $n - 1$ . When removing  $n - 1$  rows and columns though, only single matrix elements remain. We evaluate if they are zero or not, and this does not require multiplications in the underlying finite field, only equality checks. When removing  $z$  rows and columns,  $(n - z) \times (n - z)$  submatrices are obtained, and computing a determinant costs  $t(n - z)$  multiplications in a finite field. There are  $2^z$  ways of choosing which rows are to be removed, and  $2^z$  ways of choosing which columns are to be removed. Therefore,  $2^z \times 2^z = 2^{2z}$  possible  $(n - z) \times (n - z)$  submatrices, totalizing  $2^{2z}$  determinants to evaluate. The cost is therefore  $2^{2z} \times t(n - z)$  multiplications for a given  $z$ . Let  $t'(z) = 2^{2z} \times t(n - z)$ . Since  $z$  ranges from 1 to  $n - 2$ , the total cost to evaluate a matrix for MDS

property will be  $t'(1) + t(2) + \dots + t'(n - 2)$ .

### 1.3.4 Abstract algebra

Aqui pretendo colocar definições de grupo, grupo abeliano, corpo etc. A parte de álgebra abstrata que não é específica de corpos finitos e que a gente geralmente vê na faculdade

### 1.3.5 Finite fields — $\text{GF}(2^m)$

**(Finite field [13])** A finite field is a field with a finite number of elements. The number of elements in the set is called the order of the field.

**(Characteristic and order [13])** A field with order  $r$  exists if and only if  $r$  is a prime power, i.e.  $r = p^m$  for some integer  $m$ , where  $p$  is a prime integer.  $p$  is called the characteristic of the field. For each prime power there is exactly one finite field, denoted by  $\text{GF}(p^m)$ .

**(Representing finite fields with prime order [13])** Elements of a finite field  $\text{GF}(p)$  can be represented by the integers  $0, 1, \dots, p - 1$ , and the field operations are integer addition modulo  $p$  and integer multiplication modulo  $p$ .

**(Representing finite fields with non-prime order [13])** For finite fields with an order  $r = p^m$  that is not prime, addition and multiplication cannot be represented by addition and multiplication modulo  $r$ , and instead other representations must be used. One of the possible representations for  $\text{GF}(p^m)$  is by means of polynomials over  $\text{GF}(p)$  with degree at most  $m - 1$ . Addition and multiplication are then defined modulo an irreducible polynomial of degree  $m$ .

**(Polynomial [13])** A polynomial over a field  $\mathbb{F}$  is an expression of the form

$$b(x) = b_{m-1}x^{m-1} + b_{m-2}x^{m-2} + \dots + b_2x^2 + b_1x + b_0,$$

where  $x$  is the indeterminate and  $b_i \in \mathbb{F}$  are the coefficients. The degree of the polynomial equals  $l$  if  $b_j = 0$  for all  $j > l$  and  $l$  is the smallest number with this property.

Note that, when using polynomials over  $\text{GF}(p)$  to represent the  $\text{GF}(p^m)$  field, the degree is at most  $m - 1$ .

In this chapter, we focus particularly on fields with characteristic  $p = 2$ , due to their wide application in cryptography.

Addition and multiplication are defined on polynomials as follows.

**(Polynomial addition [13])** Summing two polynomials  $a(x)$  and  $b(x)$  consists of summing the coefficients with equal powers of  $x$ , with the sum occurring in the underlying field  $\mathbb{F}$ . The neutral element is 0 (the polynomial with all coefficients equal to 0). The inverse element can be found by replacing each coefficient by its inverse element in  $\mathbb{F}$ . The degree of  $a(x) + b(x)$  is at most the maximum of the degrees of  $a(x)$  and  $b(x)$ , therefore addition is closed.

For polynomials over GF(2) stored as integers in a cryptographic software implementation, addition can be implemented with a bitwise XOR instruction.

**(Polynomial multiplication [13])** *In order to make multiplication closed, we select a polynomial  $p(x)$  of degree  $l$ , called the reduction polynomial. Multiplication of  $a(x)$  and  $b(x)$  is then defined as the algebraic product of the polynomials modulo the reduction polynomial  $p(x)$ .*

*The neutral element is 1 (the polynomial of degree 0 and with coefficient of  $x^0$  equal to 1). The inverse element of  $a(x)$  is  $a^{-1}(x)$  such that  $a(x) \times a^{-1}(x) = 1 \bmod p(x)$ . Note that  $a^{-1}(x)$  exists only when  $a(x) \neq 0$ .*

For polynomials over GF(2) stored as integers in a cryptographic software implementation, multiplication by  $x$  can be implemented as a logical bit shift followed by conditional XOR (i.e subtraction) of the reduction polynomial (the **xtime** operation). Multiplication by other polynomials can be implemented as a series of **xtime**.

The reduction polynomial is chosen as an irreducible polynomial.

**(Irreducible polynomial [13])** *A polynomial  $d(x)$  is irreducible over the field  $GF(p)$  if and only if there exist no two polynomials  $a(x)$  and  $b(x)$  with coefficients in  $GF(p)$  such that  $d(x) = a(x) \times b(x)$ , where  $a(x)$  and  $b(x)$  are of degree greater than 0.*

For further reference on abstract algebra and Finite Fields, the reader may refer to [20], [22] and [21].

### 1.3.6 Computational cost unit

#### Computational cost of multiplication in GF(2<sup>8</sup>)

Consider  $T$  a state byte, which we multiply by the polynomial  $2e_x = 00101110_2 = x^5 + x^3 + x^2 + x$  in GF(2<sup>8</sup>). Note that

$$T \cdot 2e_x = T \cdot x^5 + T \cdot x^3 + T \cdot x^2 + T \cdot x = T \cdot x \cdot x \cdot x \cdot x \cdot x + T \cdot x \cdot x \cdot x + T \cdot x \cdot x + T \cdot x,$$

where  $\cdot$  denotes multiplication and  $+$  denotes addition (which, in GF(2<sup>8</sup>), is equivalent to a bitwise XOR). Multiplication by the  $x$  polynomial is performed by **xtime**, and addition is performed by **xor**.

Let  $T \cdot x = Y$ . Then  $T \cdot 2e_x = Y + Y \cdot x + Y \cdot x \cdot x + Y \cdot x \cdot x \cdot x$ .

Let  $Y \cdot x = W$ . Then  $T \cdot 2e_x = Y + W + W \cdot x + W \cdot x \cdot x$ .

Let  $W \cdot x = Z$ . Then  $T \cdot 2e_x = Y + W + Z + Z \cdot x$ .

The total number of **xtime** operations in this process is 5 (1 to obtain  $Y$  from  $T$ , 1 to obtain  $W$  from  $Y$ , 1 to obtain  $Z$  from  $W$ , 2 to compute  $Z \cdot x$ ), since we can reuse intermediate **xtime** calls. The total number of **xor** operations is 3. For multiplication in GF(2<sup>8</sup>), in the worst case, 7 **xtime** would be necessary, since the maximum degree of polynomials in GF(2<sup>8</sup>) is 7.

### Computational cost of a matrix

The computational cost of an  $n \times n$  matrix  $A$  is given by the necessary **xor** and **xtime** operations when multiplying a  $n \times 1$  column vector by  $A$ . As an example, we calculate the cost of matrix (1.5), used in the SQUARE [11] cipher.

A row of matrix (1.5) contains the elements  $01_x = 1$ ,  $02_x = x$  and  $03_x = x+1$  only. Multiplying by  $01_x$  does not require **xtime** or **xor**, since  $01_x \cdot T = T$ . Computing  $02_x \cdot T = x \cdot T$  requires 1 **xtime**. Computing  $03_x \cdot T = (x+1) \cdot T = T \cdot x + T$  requires 1 **xtime** and 1 **xor**. Furthermore, adding the row multiplication results costs 3 **xor**. Therefore, the cost of a row is 2 **xtime** and 4 **xor**. Equation 1.2 illustrates this, with  $t_1, t_2, t_3$  and  $t_4$  being bytes of the state column vector.

$$\begin{bmatrix} 02_x & 01_x & 01_x & 03_x \end{bmatrix} \cdot \begin{bmatrix} t_1 \\ t_2 \\ t_3 \\ t_4 \end{bmatrix} = 02_x \cdot t_1 + 01_x \cdot t_2 + 01_x \cdot t_3 + 03_x \cdot t_4 \quad (1.2)$$

Note that matrix (1.5) contains 4 rows, yielding a total cost of 8 **xtime** and 16 **xor**.

## 1.4 MDS matrix catalogue

In Table 1.2, the **Ord** column refers to the matrix dimensions, the **Inv** column refers to whether they are involutory or not, **Use** refers to application in e.g a block cipher or hash function, **Bib** contains the bibliographic reference, **#xor** refers to the necessary amount of **xor** operations, and **#xtime** refers to the necessary amount of **xtime** operations. All finite fields of Table 1.2 have characteristic  $p = 2$ . The order is  $2^m$ , with  $m$  being given by the degree of the irreducible polynomial in the column  $GF(2)[x]/(p(x))$ . For example,  $m = 8$  for SHARK, SQUARE, BKSQ, KHAZAD, ANUBIS, Hierocrypt, Rijndael and the Cauchy matrix found by [26].

Year	Ord	Type	Inv	Use	Bib	$GF(2)[x]/(p(x))$	#xor	#xtime	Matrices
1996	8	—	no	SHARK	[23]	$x^8 + x^7 + x^6 + x^5 + x^4 + x^2 + 1$	235 223	369 393	(1.3) (1.4)
1997	4	right circulant	no	SQUARE	[11]	$x^8 + x^7 + x^6 + x^5 + x^4 + x^2 + 1$	16 40	8 48	(1.5) (1.6)
1997	8	Cauchy	yes	—	[26]	$x^8 + x^4 + x^3 + x^2 + 1$	240	344	(1.7)
1998	3	right circulant	no	BKSQ	[12]	$x^8 + x^7 + x^6 + x^5 + x^4 + x^2 + 1$	9 39	9 63	(1.13) (1.14)
1999	4	right circulant	no	Rijndael (AES)	[13]	$x^8 + x^4 + x^3 + x + 1$	16 40	8 48	(1.11) (1.12)
2000	8	Hadamard	yes	KHAZAD	[3]	$x^8 + x^4 + x^3 + x^2 + 1$	112	120	(1.8)
2000	4	Hadamard	yes	ANUBIS	[2]	$x^8 + x^4 + x^3 + x^2 + 1$	16	20	(1.9)

2000	4	Vandermonde	no	ANUBIS key schedule	[2]	$x^8 + x^4 + x^3 + x^2 + 1$	20	32	(1.10)
2000	4	right circulant	no	Hierocrypt-3, Hierocrypt-L1	[9], [10]	$x^8 + x^6 + x^5 + x + 1$	52	108	(1.15)
							52	104	(1.16)
2000	4	right circulant	no	Hierocrypt-3	[9]	$x^4 + x + 1$	32	40	(1.17)
							40	44	(1.18)
2000	2	—	no	Hierocrypt-L1	[10]	$x^4 + x + 1$	8	10	(1.19)
							7	11	(1.20)
2004	4	—	no	FOX	[16]	$x^8 + x^7 + x^6 + x^5 + x^4 + x^3 + 1$	30	25	(1.21)
							72	106	(1.23)
2004	8	—	no	FOX	[16]	$x^8 + x^7 + x^6 + x^5 + x^4 + x^3 + 1$	141	169	(1.22)
							284	392	(1.24)
2007	3	—	yes	Curupira	[4]	$x^8 + x^6 + x^3 + x^2 + 1$	12	15	(1.25)
2007	3	right circulant	no	Curupira key schedule	[4]	$x^8 + x^6 + x^3 + x^2 + 1$	27	36	(1.26)
2009	8	right circulant	no	Grøstl	[14]	$x^8 + x^4 + x^3 + x + 1$	104	96	(1.27)
2010	8	dyadic	no	Whirlwind	[1]	$x^4 + x + 1$	104	136	(1.28)
2010	8	dyadic	no	Whirlwind	[1]	$x^4 + x + 1$	128	128	(1.29)

Table 1.2: MDS matrices: parameters, usage and cos

Please note that matrices (1.35) to (1.48) and others derived from them are also MDS, although not yet listed in Table 1.2. See Section 1.6 for further detail on this. Matrix (1.3) and its inverse (1.4) are used in the SHARK [23] cipher.

$$\begin{bmatrix}
 ce_x & 95_x & 57_x & 82_x & 8a_x & 19_x & b0_x & 01_x \\
 e7_x & fe_x & 05_x & d2_x & 52_x & c1_x & 88_x & f1_x \\
 b9_x & da_x & 4d_x & d1_x & 9e_x & 17_x & 83_x & 86_x \\
 d0_x & 9d_x & 26_x & 2c_x & 5d_x & 9f_x & 6d_x & 75_x \\
 52_x & a9_x & 07_x & 6c_x & b9_x & 8f_x & 70_x & 17_x \\
 87_x & 28_x & 3a_x & 5a_x & f4_x & 33_x & 0b_x & 6c_x \\
 74_x & 51_x & 15_x & cf_x & 09_x & a4_x & 62_x & 09_x \\
 0b_x & 31_x & 7f_x & 86_x & be_x & 05_x & 83_x & 34_x
 \end{bmatrix} \quad (1.3)$$

$$\begin{bmatrix}
 e7_x & 30_x & 90_x & 85_x & d0_x & 4b_x & 91_x & 41_x \\
 53_x & 95_x & 9b_x & a5_x & 96_x & bc_x & a1_x & 68_x \\
 02_x & 45_x & f7_x & 65_x & 5c_x & 1f_x & b6_x & 52_x \\
 a2_x & ca_x & 22_x & 94_x & 44_x & 63_x & 2a_x & a2_x \\
 fc_x & 67_x & 8e_x & 10_x & 29_x & 75_x & 85_x & 71_x \\
 24_x & 45_x & a2_x & cf_x & 2f_x & 22_x & c1_x & 0e_x \\
 a1_x & f1_x & 71_x & 40_x & 91_x & 27_x & 18_x & a5_x \\
 56_x & f4_x & af_x & 32_x & d2_x & a4_x & dc_x & 71_x
 \end{bmatrix} \quad (1.4)$$

Matrix (1.5) and its inverse (1.6) are used in the SQUARE [11] cipher. They are right-circulant.

$$\begin{bmatrix} 02_x & 01_x & 01_x & 03_x \\ 03_x & 02_x & 01_x & 01_x \\ 01_x & 03_x & 02_x & 01_x \\ 01_x & 01_x & 03_x & 02_x \end{bmatrix} \quad (1.5)$$

$$\begin{bmatrix} 0e_x & 09_x & 0d_x & 0b_x \\ 0b_x & 0e_x & 09_x & 0d_x \\ 0d_x & 0b_x & 0e_x & 09_x \\ 09_x & 0d_x & 0b_x & 0e_x \end{bmatrix} \quad (1.6)$$

Matrix (1.7) is involutory, and was obtained by [26] with a Cauchy construction.

$$\begin{bmatrix} 93_x & 13_x & 57_x & da_x & 58_x & 47_x & 0c_x & 1f_x \\ 13_x & 93_x & da_x & 57_x & 47_x & 58_x & 1f_x & 0c_x \\ 57_x & da_x & 93_x & 13_x & 0c_x & 1f_x & 58_x & 47_x \\ da_x & 57_x & 13_x & 93_x & 1f_x & 0c_x & 47_x & 58_x \\ 58_x & 47_x & 0c_x & 1f_x & 93_x & 13_x & 57_x & da_x \\ 47_x & 58_x & 1f_x & 0c_x & 13_x & 93_x & da_x & 57_x \\ 0c_x & 1f_x & 58_x & 47_x & 57_x & da_x & 93_x & 13_x \\ 1f_x & 0c_x & 47_x & 58_x & da_x & 57_x & 13_x & 93_x \end{bmatrix} \quad (1.7)$$

Matrix (1.8) is Hadamard and involutory. It is used in the KHAZAD [3] cipher.

$$\begin{bmatrix} 01_x & 03_x & 04_x & 05_x & 06_x & 08_x & 0b_x & 07_x \\ 03_x & 01_x & 05_x & 04_x & 08_x & 06_x & 07_x & 0b_x \\ 04_x & 05_x & 01_x & 03_x & 0b_x & 07_x & 06_x & 08_x \\ 05_x & 04_x & 03_x & 01_x & 07_x & 0b_x & 08_x & 06_x \\ 06_x & 08_x & 0b_x & 07_x & 01_x & 03_x & 04_x & 05_x \\ 08_x & 06_x & 07_x & 0b_x & 03_x & 01_x & 05_x & 04_x \\ 0b_x & 07_x & 06_x & 08_x & 04_x & 05_x & 01_x & 03_x \\ 07_x & 0b_x & 08_x & 06_x & 05_x & 04_x & 03_x & 01_x \end{bmatrix} \quad (1.8)$$

Matrix (1.9) is Hadamard and involutory. It is used in the ANUBIS [2] cipher.

$$\begin{bmatrix} 01_x & 02_x & 04_x & 06_x \\ 02_x & 01_x & 06_x & 04_x \\ 04_x & 06_x & 01_x & 02_x \\ 06_x & 04_x & 02_x & 01_x \end{bmatrix} \quad (1.9)$$

Still regarding the ANUBIS cipher, while (1.9) is used as its linear transformation layer, (1.10) is used in the key extraction. It is a Vandermonde construction. When  $N = 4$ , it is an MDS matrix (see Theorem 2).

$$\begin{bmatrix} 01_x & 01_x & 01_x & \dots & 01_x \\ 01_x & 02_x & 02_x^2 & \dots & 02_x^{N-1} \\ 01_x & 06_x & 06_x^2 & \dots & 06_x^{N-1} \\ 01_x & 08_x & 08_x^2 & \dots & 08_x^{N-1} \end{bmatrix} = \begin{bmatrix} 01_x & 01_x & 01_x & 01_x \\ 01_x & 02_x & 04_x & 08_x \\ 01_x & 06_x & 14_x & 78_x \\ 01_x & 08_x & 40_x & 3a_x \end{bmatrix} \text{ for } N = 4 \quad (1.10)$$

Matrix (1.11) and its inverse (1.12) are used in the Rijndael [13] cipher, which was selected to become AES. They are right-circulant. We show the hexadecimal notation and the corresponding polynomials to emphasize that, albeit stored as integers in cryptographic software implementation, all matrix elements are actually polynomials in a Finite Field. This applies not only to the Rijndael cipher's matrices but to all matrices listed in this work.

$$\begin{bmatrix} 02_x & 03_x & 01_x & 01_x \\ 01_x & 02_x & 03_x & 01_x \\ 01_x & 01_x & 02_x & 03_x \\ 03_x & 01_x & 01_x & 02_x \end{bmatrix} = \begin{bmatrix} x & x+1 & 1 & 1 \\ 1 & x & x+1 & 1 \\ 1 & 1 & x & x+1 \\ x+1 & 1 & 1 & x \end{bmatrix} \quad (1.11)$$

$$\begin{bmatrix} 0e_x & 0b_x & 0d_x & 09_x \\ 09_x & 0e_x & 0b_x & 0d_x \\ 0d_x & 09_x & 0e_x & 0b_x \\ 0b_x & 0d_x & 09_x & 0e_x \end{bmatrix} = \begin{bmatrix} x^3+x^2+x & x^3+x+1 & x^3+x^2+1 & x^3+1 \\ x^3+1 & x^3+x^2+x & x^3+x+1 & x^3+x^2+1 \\ x^3+x^2+1 & x^3+1 & x^3+x^2+x & x^3+x+1 \\ x^3+x+1 & x^3+x^2+1 & x^3+1 & x^3+x^2+x \end{bmatrix} \quad (1.12)$$

Furthermore, it is interesting to note that Rijndael's matrix (1.11) is the transpose of SQUARE's matrix (1.5) and this also happens to the inverses (matrix (1.6) is the transpose of (1.12)).

Matrices (1.13) and its inverse (1.14) are used in the BKSQ [12] cipher. They are right-circulant.

$$\begin{bmatrix} 03_x & 02_x & 02_x \\ 02_x & 03_x & 02_x \\ 02_x & 02_x & 03_x \end{bmatrix} \quad (1.13)$$

$$\begin{bmatrix} ac_x & ad_x & ad_x \\ ad_x & ac_x & ad_x \\ ad_x & ad_x & ac_x \end{bmatrix} \quad (1.14)$$

The Hierocrypt-3 cipher makes use of two MDS matrices, one for lower level diffusion and another for higher level diffusion on the cipher, which follows a nested Substitution Permutation Network design (for more detail the reader may refer to [9]). Matrix (1.15) and its inverse (1.16) are used for lower level diffusion. (1.17) and (1.18) (the inverse) are used for higher level diffusion. It is worth noting that, for lower level diffusion, the finite field is  $GF(2^8)$ , whilst, for higher level diffusion, the authors choose  $GF(2^4)$ .

$$\begin{bmatrix} c4_x & 65_x & c8_x & 8b_x \\ 8b_x & c4_x & 65_x & c8_x \\ c8_x & 8b_x & c4_x & 65_x \\ 65_x & c8_x & 8b_x & c4_x \end{bmatrix} \quad (1.15)$$

$$\begin{bmatrix} 82_x & c4_x & 34_x & f6_x \\ f6_x & 82_x & c4_x & 34_x \\ 34_x & f6_x & 82_x & c4_x \\ c4_x & 34_x & f6_x & 82_x \end{bmatrix} \quad (1.16)$$

$$\begin{bmatrix} 5_x & 5_x & a_x & e_x \\ e_x & 5_x & 5_x & a_x \\ a_x & e_x & 5_x & 5_x \\ 5_x & a_x & e_x & 5_x \end{bmatrix} \quad (1.17)$$

$$\begin{bmatrix} b_x & e_x & e_x & 6_x \\ 6_x & b_x & e_x & e_x \\ e_x & 6_x & b_x & e_x \\ e_x & e_x & 6_x & b_x \end{bmatrix} \quad (1.18)$$

The Hierocrypt-L1 cipher too uses matrix (1.15) and the inverse (1.16) in its lower diffusion layer. However, for the higher layer, (1.19) and (1.20) (inverse) are used. Analogously to Hierocrypt-3, the higher layer uses  $GF(2^4)$ .

$$\begin{bmatrix} 5_x & 7_x \\ a_x & b_x \end{bmatrix} \quad (1.19)$$

$$\begin{bmatrix} c_x & a_x \\ 5_x & b_x \end{bmatrix} \quad (1.20)$$

Matrices (1.21) (inverse: (1.23)) and (1.22) (inverse: (1.24)) are used in the FOX block cipher family, with  $z = x^7 + x^6 + x^5 + x^4 + x^3 + x^2 + 1$ ,  $a = x + 1$ ,  $b = x^7 + x$ ,  $c = x$ ,  $d = x^2$ ,  $e = x^7 + x^6 + x^5 + x^4 + x^3 + x^2$  and  $f = x^6 + x^5 + x^4 + x^3 + x^2 + x$ .

$$\begin{bmatrix} 1 & 1 & 1 & x \\ 1 & z & x & 1 \\ z & x & 1 & 1 \\ x & 1 & z & 1 \end{bmatrix} = \begin{bmatrix} 01_x & 01_x & 01_x & 02_x \\ 01_x & fd_x & 02_x & 01_x \\ fd_x & 02_x & 01_x & 01_x \\ 02_x & 01_x & fd_x & 01_x \end{bmatrix} \quad (1.21)$$

$$\begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & a \\ 1 & a & b & c & d & e & f & 1 \\ a & b & c & d & e & f & 1 & 1 \\ b & c & d & e & f & 1 & a & 1 \\ c & d & e & f & 1 & a & b & 1 \\ d & e & f & 1 & a & b & c & 1 \\ e & f & 1 & a & b & c & d & 1 \\ f & 1 & a & b & c & d & e & 1 \end{bmatrix} = \begin{bmatrix} 01_x & 01_x & 01_x & 01_x & 01_x & 01_x & 01_x & 03_x \\ 01_x & 03_x & 82_x & 02_x & 04_x & fc_x & 7e_x & 01_x \\ 03_x & 82_x & 02_x & 04_x & fc_x & 7e_x & 01_x & 01_x \\ 82_x & 02_x & 04_x & fc_x & 7e_x & 01_x & 03_x & 01_x \\ 02_x & 04_x & fc_x & 7e_x & 01_x & 03_x & 82_x & 01_x \\ 04_x & fc_x & 7e_x & 01_x & 03_x & 82_x & 02_x & 01_x \\ fc_x & 7e_x & 01_x & 03_x & 82_x & 02_x & 04_x & 01_x \\ 7e_x & 01_x & 03_x & 82_x & 02_x & 04_x & fc_x & 01_x \end{bmatrix} \quad (1.22)$$



$$\begin{bmatrix} 7e_x & e1_x & ad_x & b0_x \\ 7e_x & ad_x & b0_x & e1_x \\ 7e_x & b0_x & e1_x & ad_x \\ c3_x & 7e_x & 7e_x & 7e_x \end{bmatrix} \quad (1.23)$$

$$\begin{bmatrix} c6_x & fe_x & 3a_x & 73_x & 6d_x & 0c_x & d2_x & b7_x \\ c6_x & 3a_x & 73_x & 6d_x & 0c_x & d2_x & b7_x & fe_x \\ c6_x & 73_x & 6d_x & 0c_x & d2_x & b7_x & fe_x & 3a_x \\ c6_x & 6d_x & 0c_x & d2_x & b7_x & fe_x & 3a_x & 73_x \\ c6_x & 0c_x & d2_x & b7_x & fe_x & 3a_x & 73_x & 6d_x \\ c6_x & d2_x & b7_x & fe_x & 3a_x & 73_x & 6d_x & 0c_x \\ c6_x & b7_x & fe_x & 3a_x & 73_x & 6d_x & 0c_x & d2_x \\ ea_x & c6_x & c6_x & c6_x & c6_x & c6_x & c6_x & c6_x \end{bmatrix} \quad (1.24)$$

Matrix (1.25) is used in Curupira's diffusion layer. It is involutory.

$$\begin{bmatrix} 03_x & 02_x & 02_x \\ 04_x & 05_x & 04_x \\ 06_x & 06_x & 07_x \end{bmatrix} \quad (1.25)$$

Matrix (1.26) is used in Curupira's key scheduling process, with  $c(x) = x^4 + x^3 + x^2$ .

$$\begin{bmatrix} 1 + c(x) & c(x) & c(x) \\ c(x) & 1 + c(x) & c(x) \\ c(x) & c(x) & 1 + c(x) \end{bmatrix} \quad (1.26)$$

Matrix (1.27) is used in the Grøstl hash function. It is right-circulant.

$$\begin{bmatrix} 02_x & 02_x & 03_x & 04_x & 05_x & 03_x & 05_x & 07_x \\ 07_x & 02_x & 02_x & 03_x & 04_x & 05_x & 03_x & 05_x \\ 05_x & 07_x & 02_x & 02_x & 03_x & 04_x & 05_x & 03_x \\ 03_x & 05_x & 07_x & 02_x & 02_x & 03_x & 04_x & 05_x \\ 05_x & 03_x & 05_x & 07_x & 02_x & 02_x & 03_x & 04_x \\ 04_x & 05_x & 03_x & 05_x & 07_x & 02_x & 02_x & 03_x \\ 03_x & 04_x & 05_x & 03_x & 05_x & 07_x & 02_x & 02_x \\ 02_x & 03_x & 04_x & 05_x & 03_x & 05_x & 07_x & 02_x \end{bmatrix} \quad (1.27)$$

Matrices (1.28) and (1.29) are used in the Whirlwind hash function.

$$\begin{bmatrix} 5_x & 4_x & a_x & 6_x & 2_x & d_x & 8_x & 3_x \\ 4_x & 5_x & 6_x & a_x & d_x & 2_x & 3_x & 8_x \\ a_x & 6_x & 5_x & 4_x & 8_x & 3_x & 2_x & d_x \\ 6_x & a_x & 4_x & 5_x & 3_x & 8_x & d_x & 2_x \\ 2_x & d_x & 8_x & 3_x & 5_x & 4_x & a_x & 6_x \\ d_x & 2_x & 3_x & 8_x & 4_x & 5_x & 6_x & a_x \\ 8_x & 3_x & 2_x & d_x & a_x & 6_x & 5_x & 4_x \\ 3_x & 8_x & d_x & 2_x & 6_x & a_x & 4_x & 5_x \end{bmatrix} \quad (1.28)$$

$$\begin{bmatrix}
5_x & e_x & 4_x & 7_x & 1_x & 3_x & f_x & 8_x \\
e_x & 5_x & 7_x & 4_x & 3_x & 1_x & 8_x & f_x \\
4_x & 7_x & 5_x & e_x & f_x & 8_x & 1_x & 3_x \\
7_x & 4_x & e_x & 5_x & 8_x & f_x & 3_x & 1_x \\
1_x & 3_x & f_x & 8_x & 5_x & e_x & 4_x & 7_x \\
3_x & 1_x & 8_x & f_x & e_x & 5_x & 7_x & 4_x \\
f_x & 8_x & 1_x & 3_x & 4_x & 7_x & 5_x & e_x \\
8_x & f_x & 3_x & 1_x & 7_x & 4_x & e_x & 5_x
\end{bmatrix} \tag{1.29}$$

## 1.5 A note on Hierocrypt 3 and Hierocrypt-L1

In the Hierocrypt 3 and Hierocrypt-L1 ciphers, there are two different diffusion layers, referred as low level ( $mds_l$ ) and high level ( $MDS_H$ ) by the authors, since these ciphers follow a nested SPN structure (for more details please refer to [9] and [10]). Their high level diffusion layer is called  $MDS_H$  and is based on multiplication by matrices (1.17) (for Hierocrypt 3) and (1.19) (for Hierocrypt-L1). They are both MDS, as stated in the design rationale section of the ciphers' specification documents (see [9] and [10]). However, for the implementation, the  $MDS_H$  transformation can be equivalently expressed as multiplication by a  $16 \times 16$  binary matrix (in Hierocrypt-3) which is *not* MDS, but yields the same result. For Hierocrypt-L1, a  $8 \times 8$  non-MDS matrix is used. In [9], they state

“ $MDS(32, 4)$  consists of eight parallel  $MDS(4, 4)$ . When all  $MDS(4, 4)$  are the same,  $MDS_H$  is nothing but the combination of byte-wise XOR's and is expressed as  $16 \times 16$  matrix.”

In [10], they present a similar statement about the  $8 \times 8$  matrix.

Matrix (1.30) is the binary matrix used for  $MDS_H$  in Hierocrypt 3. We can see that it is not MDS, since it has a zero element (see Theorem 2).

$$\begin{bmatrix}
1010101011011111 \\
1101110111100111 \\
1110111011110011 \\
0101010110101110 \\
1111101010101101 \\
0111110111011110 \\
0011111011101111 \\
1110010101011010 \\
1101111110101010 \\
1110011111011101 \\
1111001111101110 \\
1010111001010101 \\
1010110111111010 \\
1101111001111101 \\
1110111100111110 \\
0101101011100101
\end{bmatrix} \tag{1.30}$$

Matrix (1.31) is also not MDS, since it has a zero element. It is used for  $MDS_H$  in Hierocrypt L1.

$$\begin{bmatrix}
10101110 \\
11011111 \\
11100111 \\
01011101 \\
11010101 \\
11101010 \\
11111101 \\
10101011
\end{bmatrix} \tag{1.31}$$

## 1.6 A note on Whirlpool-0

Matrix (1.32) is used in the Whirlpool-0 hash function. The irreducible polynomial of the field is  $p(x) = x^8 + x^4 + x^3 + x^2 + 1$ , and the inverse matrix is (1.33).

$$\begin{bmatrix}
01_x & 01_x & 03_x & 01_x & 05_x & 08_x & 09_x & 05_x \\
05_x & 01_x & 01_x & 03_x & 01_x & 05_x & 08_x & 09_x \\
09_x & 05_x & 01_x & 01_x & 03_x & 01_x & 05_x & 08_x \\
08_x & 09_x & 05_x & 01_x & 01_x & 03_x & 01_x & 05_x \\
05_x & 08_x & 09_x & 05_x & 01_x & 01_x & 03_x & 01_x \\
01_x & 05_x & 08_x & 09_x & 05_x & 01_x & 01_x & 03_x \\
03_x & 01_x & 05_x & 08_x & 09_x & 05_x & 01_x & 01_x \\
01_x & 03_x & 01_x & 05_x & 08_x & 09_x & 05_x & 01_x
\end{bmatrix} \tag{1.32}$$

$$\begin{bmatrix}
a5_x & 07_x & 95_x & 9e_x & 0c_x & a7_x & 01_x & ea_x \\
d1_x & b3_x & e8_x & 5a_x & 01_x & ab_x & 3d_x & 6c_x \\
f8_x & 3c_x & 8a_x & 12_x & 2e_x & 8b_x & cc_x & 5e_x \\
73_x & 27_x & 4e_x & e0_x & bf_x & c0_x & 24_x & 4a_x \\
85_x & 17_x & 1c_x & 47_x & 0d_x & 4e_x & 5b_x & aa_x \\
17_x & b0_x & d6_x & 2d_x & 6c_x & 26_x & ef_x & cb_x \\
dd_x & ce_x & 15_x & da_x & 6c_x & 17_x & 03_x & fc_x \\
ec_x & 78_x & d8_x & ea_x & da_x & 21_x & 17_x & b1_x
\end{bmatrix} \quad (1.33)$$

In [25], it is claimed that (1.32) is MDS. However, in [24], Shirai and Shibutani find singular submatrices, which implies that the matrix is, in fact, not MDS. They also present alternative circulant matrices which are MDS.

One of the singular submatrices found in [24] is matrix (1.34). Other singular submatrices were found, for further detail we refer the reader to [24].

$$\begin{bmatrix}
01_x & 05_x \\
01_x & 05_x
\end{bmatrix} \quad (1.34)$$

Furthermore, Shirai and Shibutani obtain 224 MDS matrices satisfying the desired conditions for Whirlpool:

- Branch number equal to 9;
- As many 1-elements as possible (namely, 3);
- Hamming weight of any element is at most 2.

Matrices from (1.35) to (1.48) are the ones obtained by Shirai. They point out that, reversing elements and applying rotations to each of the  $C_i$ , it is possible to obtain additional MDS matrices, totalizing thus 224 MDS matrices. For further detail please refer to [24]. The authors of Whirlpool decided to replace the non-MDS matrix by Shirai's  $C_7$  matrix, and therefore Whirlpool-0 refers to the version with the non-MDS matrix, prior to the correction, and Whirlpool refers to the corrected version, with the MDS matrix.

$$C_0 = rcirc(01_x, 01_x, 02_x, 01_x, 05_x, 08_x, 09_x, 04_x) \quad (1.35)$$

$$C_1 = rcirc(01_x, 01_x, 02_x, 01_x, 06_x, 09_x, 08_x, 03_x) \quad (1.36)$$

$$C_2 = rcirc(01_x, 01_x, 02_x, 01_x, 08_x, 09_x, 04_x, 05_x) \quad (1.37)$$

$$C_3 = rcirc(01_x, 01_x, 02_x, 01_x, 09_x, 06_x, 04_x, 03_x) \quad (1.38)$$

$$C_4 = rcirc(01_x, 01_x, 02_x, 06_x, 05_x, 09_x, 01_x, 08_x) \quad (1.39)$$

$$C_5 = rcirc(01_x, 01_x, 03_x, 01_x, 04_x, 09_x, 05_x, 06_x) \quad (1.40)$$

$$C_6 = rcirc(01_x, 01_x, 03_x, 01_x, 08_x, 04_x, 09_x, 06_x) \quad (1.41)$$

$$C_7 = rcirc(01_x, 01_x, 04_x, 01_x, 08_x, 05_x, 02_x, 09_x) \quad (1.42)$$

$$C_8 = rcirc(01_x, 01_x, 04_x, 03_x, 06_x, 08_x, 01_x, 09_x) \quad (1.43)$$

$$C_9 = rcirc(01_x, 01_x, 04_x, 03_x, 06_x, 08_x, 01_x, 09_x) \quad (1.44)$$

$$C_{10} = rcirc(01_x, 01_x, 05_x, 01_x, 04_x, 06_x, 03_x, 09_x) \quad (1.45)$$

$$C_{11} = rcirc(01_x, 01_x, 05_x, 08_x, 02_x, 09_x, 01_x, 06_x) \quad (1.46)$$

$$C_{12} = rcirc(01_x, 01_x, 08_x, 01_x, 06_x, 03_x, 02_x, 09_x) \quad (1.47)$$

$$C_{13} = rcirc(01_x, 01_x, 08_x, 02_x, 04_x, 05_x, 01_x, 09_x) \quad (1.48)$$

## 1.7 Non-MDS matrix catalogue

Table 1.3 presents matrices which were reported in the literature for usage in symmetric block ciphers (or hash functions) but are not MDS. It shows their **xor** and **xtime** costs, as well as the respective branch numbers. Column **Ord** refers to the matrix dimensions, **Bib** contains the bibliographic reference, **#xor** and **#xtime** refer to the required amount of **xor** and **xtime** operations, i.e the costs, and  $\mathcal{B}(\theta)$  presents the branch number.

Fiquei em dúvida quando fui calcular o branch number das matrizes binárias do Hierocrypt, podemos revisar isso na próxima reunião? Obrigada!

Year	Ord	Bib	Type	Use	$\mathcal{B}(\theta)$	#xor	#xtime	Matrix
2000	16	[9]	binary	Hierocrypt-3	branch	160	0	(1.30)
2000	8	[10]	binary	Hierocrypt-L1	branch	37	0	(1.31)
2003	8	[25]	right	Whirlpool-0	8	89	87	(1.32)
			circulant			247	366	(1.33)

Table 1.3: Non-MDS matrices: parameters, usage and costs.

## 1.8 About the irreducible polynomials

to be written

## 1.9 Computing xtime and xor of the matrices

One can compute the costs manually, however, the following following C code can also be used for this purpose, considering that polynomials in  $GF(2^8)$  are stored in integers (a set bit means coefficient equal to 1, a zero bit means coefficient equal to 0).

For e.g SHARK and SQUARE, the field order is equal to 8, therefore ORDER must be set to 8 and DEGREE\_LIMIT\_MASK must be set to  $x^8$ .

```
#define DEGREE_LIMIT_MASK 0x100
#define ORDER 8
```

The following function obtains the amount of **xtime** required to multiply by the polynomial.

```
unsigned int poly_xtime_cost(unsigned int poly) {
    unsigned int degree_mask = DEGREE_LIMIT_MASK;
    unsigned int degree = ORDER;
    while ((poly & degree_mask) == 0) {
        degree_mask >>= 1;
        degree--;
    }
    return degree;
}
```

The following function obtains the amount of **xor** required to multiply by the polynomial.

```
unsigned int poly_xor_cost(unsigned int poly) {
    unsigned int mask = 1;
    unsigned int set_bits = 0;
    unsigned int current_bit = 0;
    while (current_bit <= ORDER) {
        set_bits += ((poly & mask) != 0);
        mask <<= 1;
        current_bit++;
    }
    return set_bits - 1;
}
```

And, to compute the **xtime** and **xor** costs of a matrix, we must sum the costs of each row, which is accomplished by the following functions. Note that for e.g SHARK DIM must be set to 8, for SQUARE, to 4, and so forth.

```
#define DIM 8
```

```
unsigned int matrix_xtime_cost(unsigned int mat [DIM][DIM]) {
    unsigned int total_cost = 0;
```

```

    for (int row = 0; row < DIM; row++) {
        unsigned int row_cost = 0;
        for (int col = 0; col < DIM; col++) {
            row_cost += poly_xtime_cost(mat[row][col]);
        }
        printf("Row %d costs %d xtime\n", row, row_cost);
        total_cost += row_cost;
    }
    printf("The full matrix costs %d xtime\n", total_cost);
    return total_cost;
}

unsigned int matrix_xor_cost(unsigned int mat[DIM][DIM]) {
    unsigned int total_cost = 0;
    for (int row = 0; row < DIM; row++) {
        unsigned int row_cost = DIM - 1; //sum elements
        for (int col = 0; col < DIM; col++) {
            row_cost += poly_xor_cost(mat[row][col]);
        }
        printf("Row %d costs %d xor\n", row, row_cost);
        total_cost += row_cost;
    }
    printf("The full matrix costs %d xor\n", total_cost);
    return total_cost;
}

```

### 1.9.1 SQUARE manual calculation example

The computational cost for matrix (1.3), used in the SQUARE cipher, was explained in Section 1.3.6.

For matrix (1.6), used in SQUARE's decryption process, each row contains elements from  $\{0e_x, 09_x, 0d_x, 0b_x\}$ .

$$0e_x = 00001110_2 = x^3 + x^2 + x \text{ requires } 3 \text{ **xtime** and } 2 \text{ **xor**}$$

$$09_x = 00001001_2 = x^3 + 1 \text{ requires } 3 \text{ **xtime** and } 1 \text{ **xor**}$$

$$0d_x = 00001101_2 = x^3 + x^2 + 1 \text{ requires } 3 \text{ **xtime** and } 2 \text{ **xor**}$$

$$0b_x = 00001011_2 = x^3 + x + 1 \text{ requires } 3 \text{ **xtime** and } 2 \text{ **xor**}$$

There are 3 **xor** to add the intermediate row multiplication results, totalizing 12 **xtime** and 10 **xor** per row. There are 4 rows, hence 48 **xtime** and 40 **xor**.

## 1.10 Conclusions

yet to be written



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