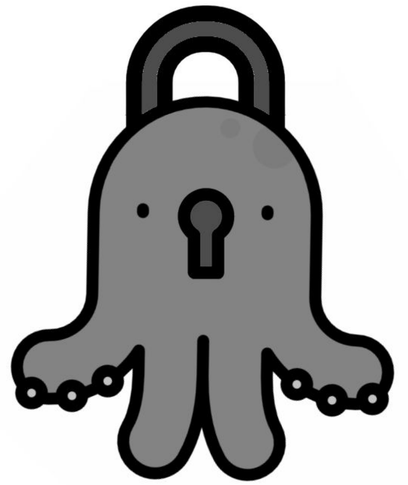
# Advanced Encryption Standard (AES)

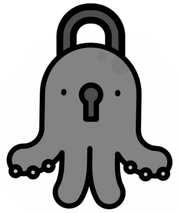
IFT 3275



# La mort de DES (1977-1997/2001):

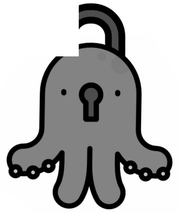

- Possibilité d’utiliser 3DES
- Pas très efficace
- Blocs de seulement 64 bits
- Possibilité d’utiliser des plus grands clefs (jusqu’à 256 bits)

NIST
National Institute of Standards and Technology

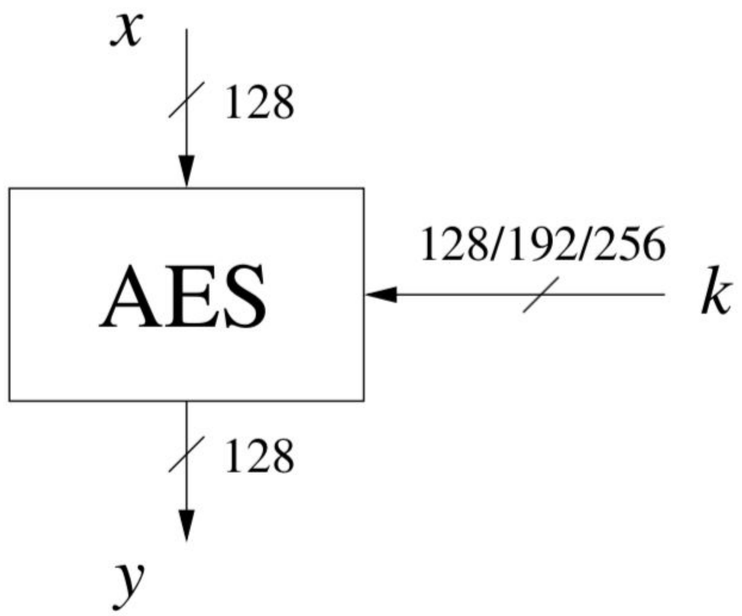


**Finalistes:**

- *Mars* by IBM Corporation
- *RC6* by RSA Laboratories
- *Rijndael*, by Joan Daemen and Vincent Rijmen
- *Serpent*, by Ross Anderson, Eli Biham and Lars Knudsen
- *Twofish*, by Bruce Schneier, John Kelsey, Doug Whiting, David Wagner, Chris Hall and Niels Ferguson

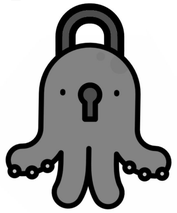


**Survol:**

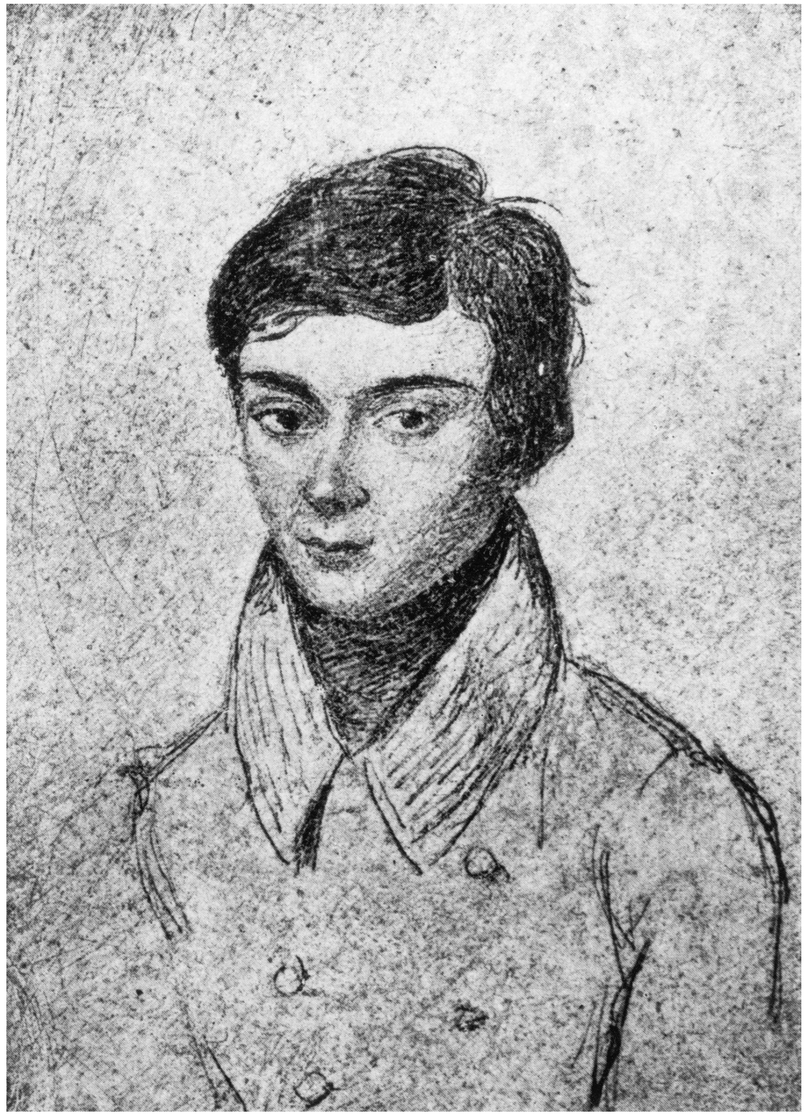


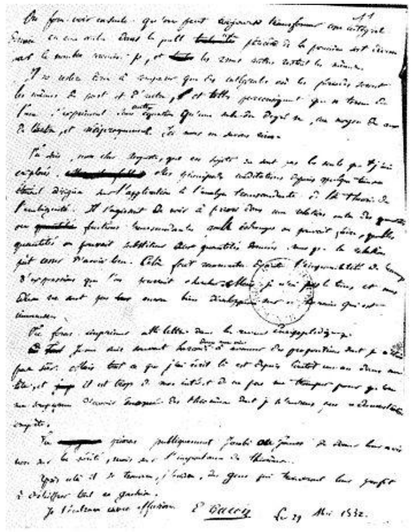

| key lengths | # rounds = $n_r$ |
|---|---|
| 128 bit | 10 |
| 192 bit | 12 |
| 256 bit | 14 |

- **Pas un réseau de Feistel (comme DES) mais bien un SPN**
- **Feistel => 64/2=32 bits qui sont encryptés par ronde vs. 128 bits pour AES**
- **A été étudié depuis la fin des années 1990 et aucune attaque plus efficace qu'une fouille exhaustive n'a été découverte (ou publiée)**
- **Très efficace**
- **Utilisé par: Internet security standard IPsec, TLS, SSH, Wi-Fi encryption (IEEE 802.11i), Skype, ExpressVPN, gouvernement american, etc.**



# Introduction brève aux corps de Galois:





**1811-1832**

**“Après cela, il y aura, j’espère, des gens qui trouveront leur profit à déchiffrer tout ce gâchis”**

# Introduction brève aux corps de Galois:

**Section incluse après le cours...**

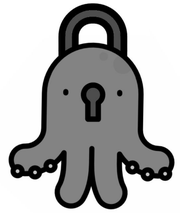
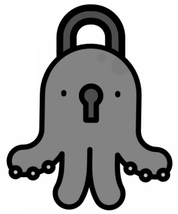


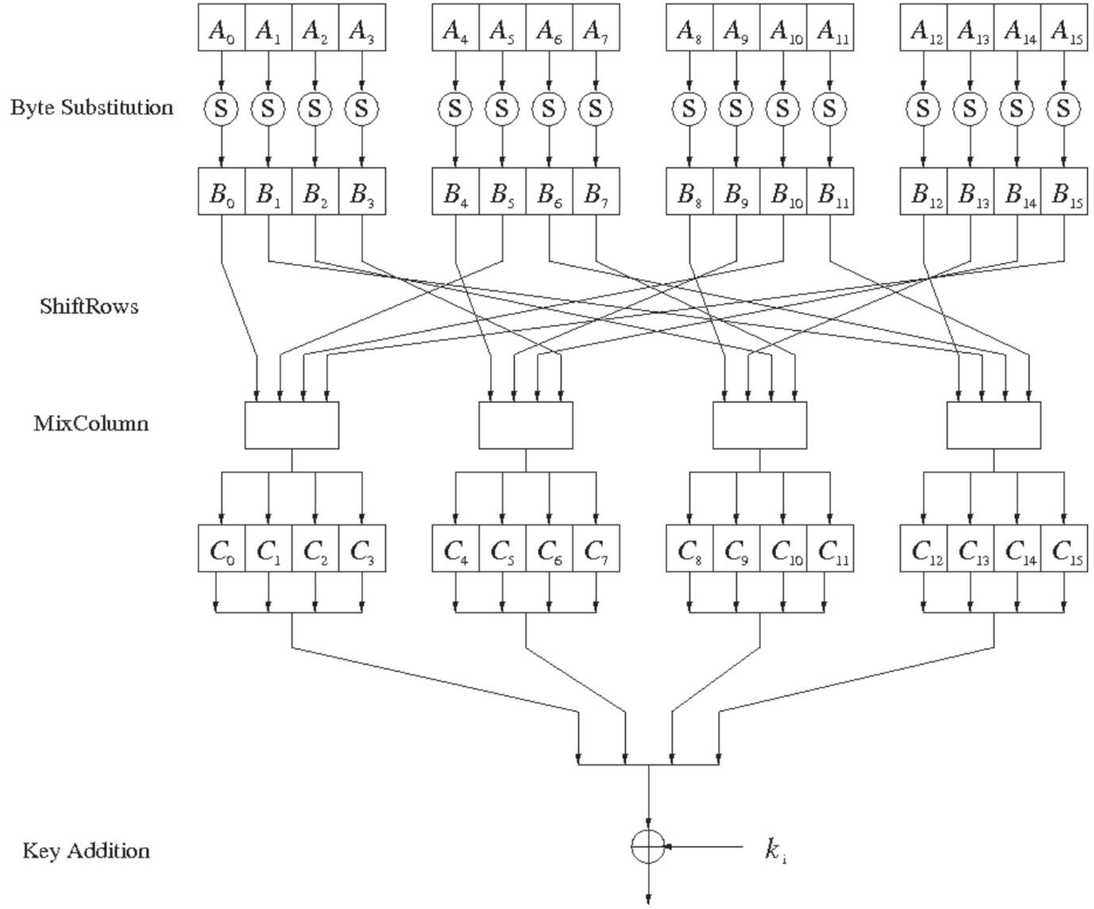
**Table 4.2** Multiplicative inverse table in $GF(2^8)$ for bytes $xy$ used within the AES S-Box

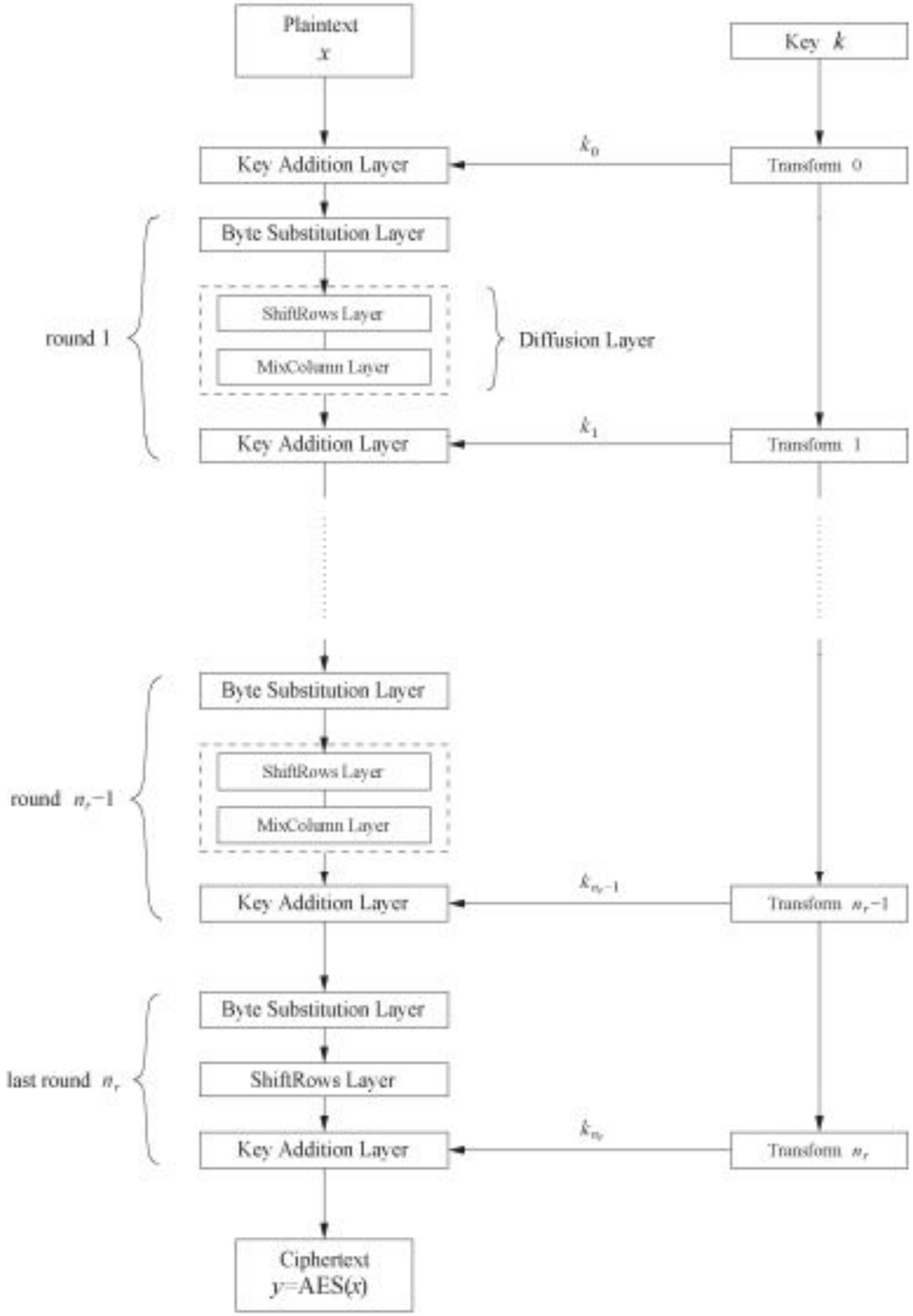
| | Y | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | A | B | C | D | E | F |
| 0 | 00 | 01 | 8D | F6 | CB | 52 | 7B | D1 | E8 | 4F | 29 | C0 | B0 | E1 | E5 | C7 |
| 1 | 74 | B4 | AA | 4B | 99 | 2B | 60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

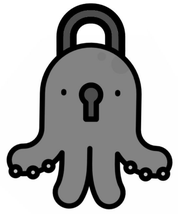


# Encryption:

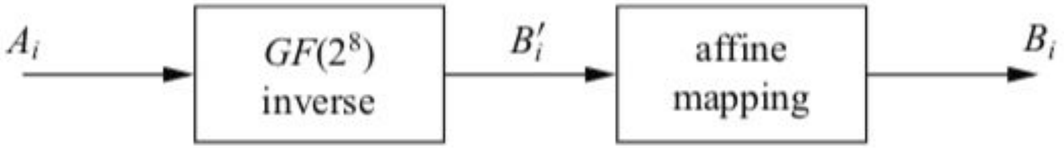
| | | | |
|---|---|---|---|
| $A_0$ | $A_4$ | $A_8$ | $A_{12}$ |
| $A_1$ | $A_5$ | $A_9$ | $A_{13}$ |
| $A_2$ | $A_6$ | $A_{10}$ | $A_{14}$ |
| $A_3$ | $A_7$ | $A_{11}$ | $A_{15}$ |



# Couche de substitution:

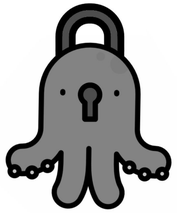



$$\begin{pmatrix} b_0 \\ b_1 \\ b_2 \\ b_3 \\ b_4 \\ b_5 \\ b_6 \\ b_7 \end{pmatrix} \equiv \begin{pmatrix} 1&0&0&0&1&1&1&1 \\ 1&1&0&0&0&1&1&1 \\ 1&1&1&0&0&0&1&1 \\ 1&1&1&1&0&0&0&1 \\ 1&1&1&1&1&0&0&0 \\ 0&1&1&1&1&1&0&0 \\ 0&0&1&1&1&1&1&0 \\ 0&0&0&1&1&1&1&1 \end{pmatrix} \begin{pmatrix} b'_0 \\ b'_1 \\ b'_2 \\ b'_3 \\ b'_4 \\ b'_5 \\ b'_6 \\ b'_7 \end{pmatrix} + \begin{pmatrix} 1 \\ 1 \\ 0 \\ 0 \\ 0 \\ 1 \\ 1 \\ 0 \end{pmatrix} \quad \text{mod } 2.$$

**Table 4.3** AES S-Box: Substitution values in hexadecimal notation for input byte $(xy)$

| $x$ \ $y$ | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | A | B | C | D | E | F |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 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 |

$$\text{ByteSub}(A) + \text{ByteSub}(B) \neq \text{ByteSub}(A + B)$$



## Couche de diffusion: Linéaire => DIFF(A) + DIFF(B) = DIFF(A+B)

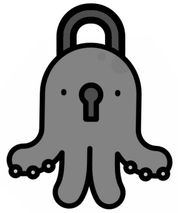
## ShiftRows:

| | | | |
|---|---|---|---|
| $B_0$ | $B_4$ | $B_8$ | $B_{12}$ |
| $B_1$ | $B_5$ | $B_9$ | $B_{13}$ |
| $B_2$ | $B_6$ | $B_{10}$ | $B_{14}$ |
| $B_3$ | $B_7$ | $B_{11}$ | $B_{15}$ |

| | | | | |
|---|---|---|---|---|
| $B_0$ | $B_4$ | $B_8$ | $B_{12}$ | no shift |
| $B_5$ | $B_9$ | $B_{13}$ | $B_1$ | ← one position left shift |
| $B_{10}$ | $B_{14}$ | $B_2$ | $B_6$ | ← two positions left shift |
| $B_{15}$ | $B_3$ | $B_7$ | $B_{11}$ | ← three positions left shift |

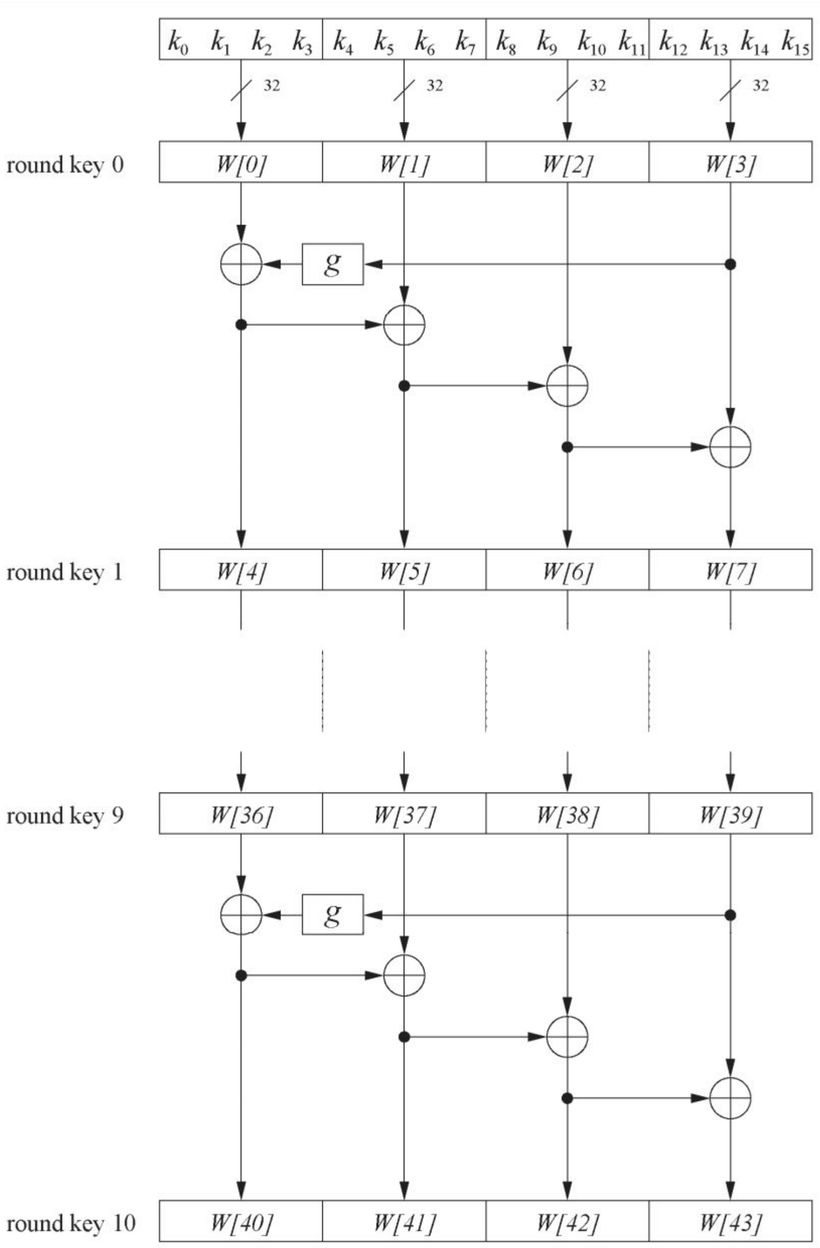
## MixColumn:

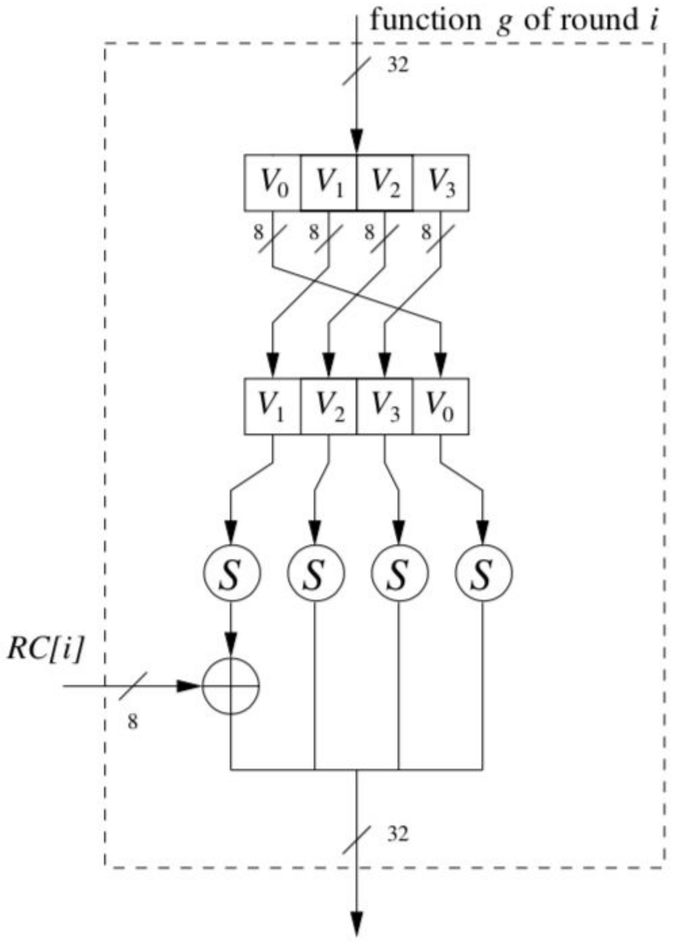
$$\begin{pmatrix} C_0 \\ C_1 \\ C_2 \\ C_3 \end{pmatrix} = \begin{pmatrix} 02\ 03\ 01\ 01 \\ 01\ 02\ 03\ 01 \\ 01\ 01\ 02\ 03 \\ 03\ 01\ 01\ 02 \end{pmatrix} \begin{pmatrix} B_0 \\ B_5 \\ B_{10} \\ B_{15} \end{pmatrix}.$$



# Génération de clefs de rondes:

| Key length (bits) | Number of subkeys |
|---|---|
| 128 | 11 |
| 192 | 13 |
| 256 | 15 |



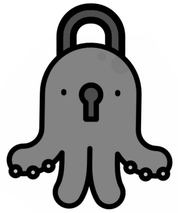

$RC[1] = x^0 = (00000001)_2$

$RC[2] = x^1 = (00000010)_2$

$RC[3] = x^2 = (00000100)_2$

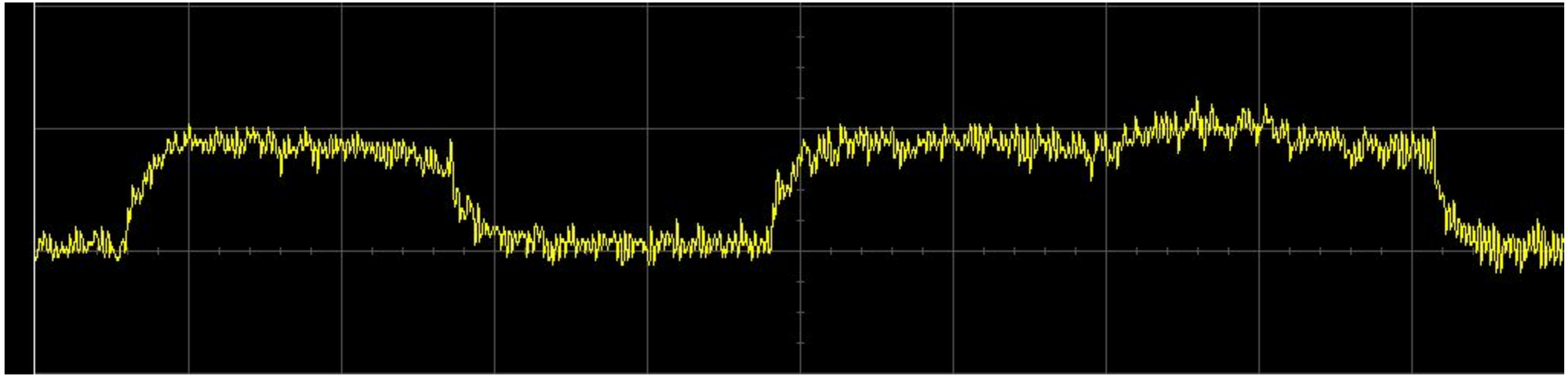
...

$RC[10] = x^9 = (00110110)_2$



**Attaque par canal auxiliaire:**

**Attaque par sondage, analyse d’émanations électromagnétiques, analyse de consommation, attaque temporelle, attaque par faute, analyse du traffic, attaque par prédiction de branches, cryptanalyse acoustique, etc.**



- **(KAT) known answer test => Principe de Kerckhoffs**