A new representation of the AES Key Schedule
Application to mixFeed

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Thursday, December 17th 2020

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Introduction

National Institute of Standards and Technology (NIST) initiated processes to solicit, evaluate, and standardize cryptographic algorithms:

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- 2019 - ... : **Lightweight Cryptography**.
  - 57 submissions.
  - 56 were selected as Round 1 Candidates.
  - 32 were selected as Round 2 Candidates.

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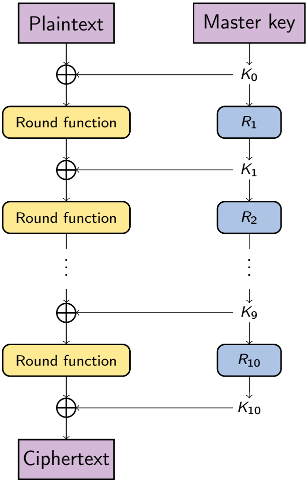

Description of the AES-128.

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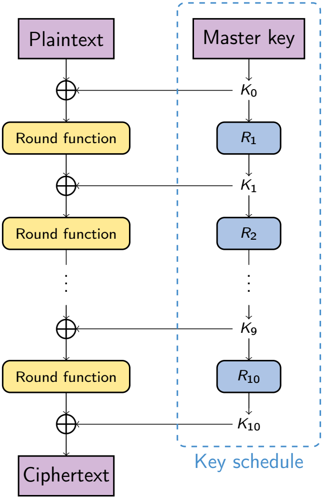
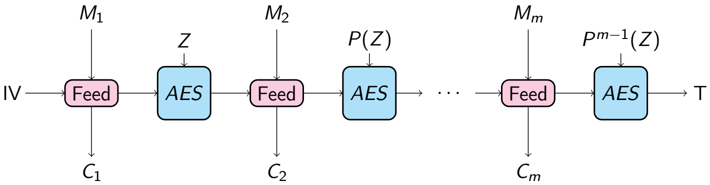


Description of the AES-128.

mixFeed [NIST LW Submission]

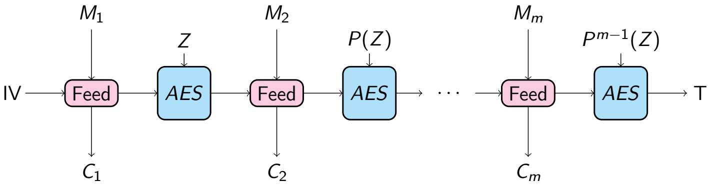
- mixFeed is a **second-round candidate** in the NIST Lightweight Standardization Process.
- It was submitted by **Bishwajit Chakraborty** and **Mridul Nandi**.
- It is an **AEAD** (Authenticated Encryption with Associated Data) algorithm.
- It is based on the AES block cipher.

mixFeed



Simplified scheme of mixFeed encryption.

mixFeed



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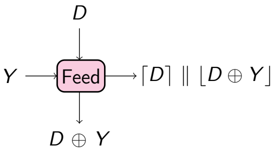
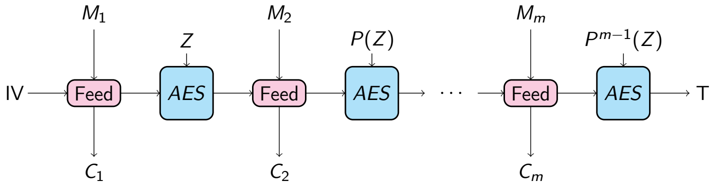


Function Feed in the case where $|D| = 128$.

mixFeed



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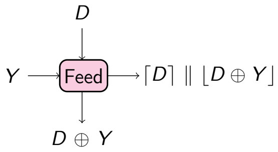

Function Feed in the case where $|D| = 128$.

P: it is the permutation corresponding to eleven rounds of AES-128 key schedule.

Mustafa Khairallah's observation [ToSC'19]

000102030405060708090a0b0c0d0e0f
00020406080a0c0e10121416181a1c1e
0004080c1014181c2024282c3034383c
00081018202830384048505860687078
0102030405060708090a0b0c0d0e0f0
101112131415161718191a1b1c1d1e1f
20222426282a2c2e30323436383a3c3e
4044484c5054585c6064686c7074787c
80889098a0a8b0b8c0c8d0d8e0e8f0f8
303132333435363738393a3b3c3d3e3f
707172737475767778797a7b7c7d7e7f
000306090c0f1215181b1e2124272a2d
00050a0f14191e23282d32373c41464b
00070e151c232a31383f464d545b6269
000d1a2734414e5b6875828f9ca9b6c3
00152a3f54697e93a8bdd2e7fc11263b
00172e455c738aa1b8cfe6fd142b4259
00183048607890a8c0d8f00820385068
001c3854708ca8c4e0fc1834506c88a4
001f3e5d7c9bbad9f81736557493b2d1

Using brute-force and out of 33 tests, Khairallah found **20 cycles of length 14018661024**[1] for the permutation P.

Surprising facts:

→ all cycles found are of the same length.

→ this length is much smaller than the cycle length expected for a 128-bit permutation.

[1] Khairallah actually reported the length as 1133759136, probably because of a 32-bit overflow

AES Key Schedule

The AES key schedule is used to derive **11 subkeys** from a master key K.

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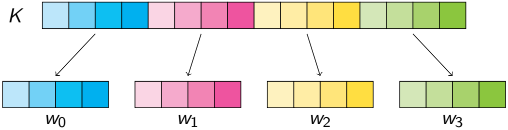

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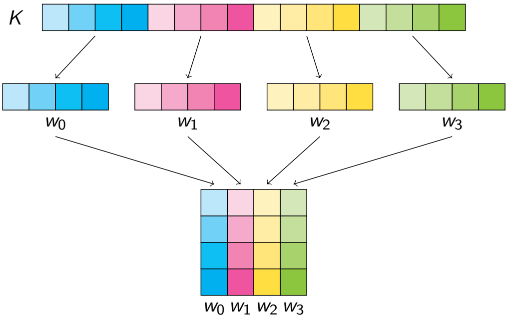

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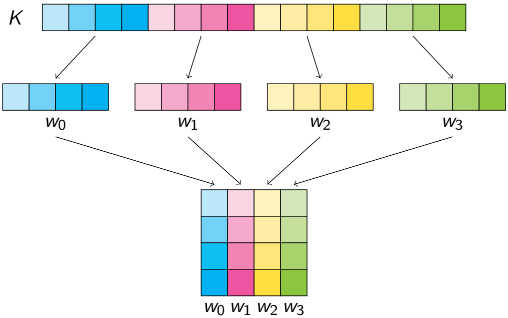
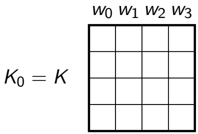


Division of the key into words and representation of the words in a matrix.

$\rightarrow$ The subkey at round i is the concatenation of the words $\mathbf{w_{4i}}$ to $\mathbf{w_{3+4i}}$.

AES Key Schedule



Construction of words $\mathbf{w_i}$ for $i \geq 4$.

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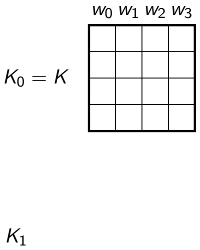

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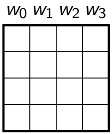
AES Key Schedule

The leftmost column:

$K_0 = K$



K_1

$$\mathbf{w_i} = \text{SubWord}(\text{RotWord}(\mathbf{w_{i-1}})) \oplus \text{RCon}(i/4) \oplus \mathbf{w_{i-4}}$$

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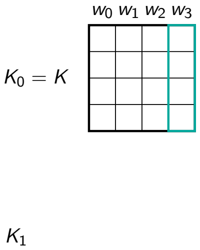

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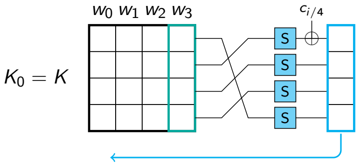

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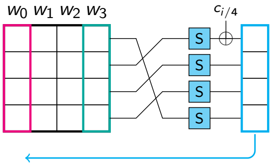

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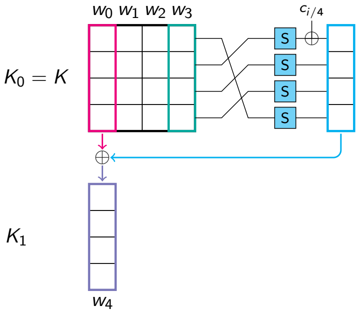

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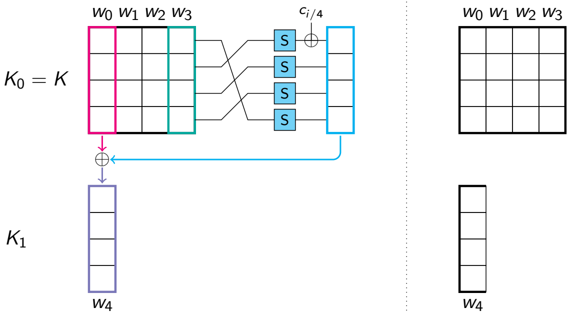

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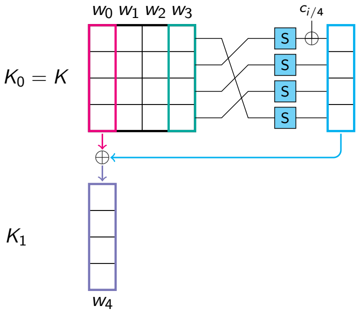

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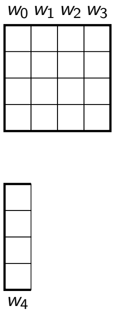
Others columns:



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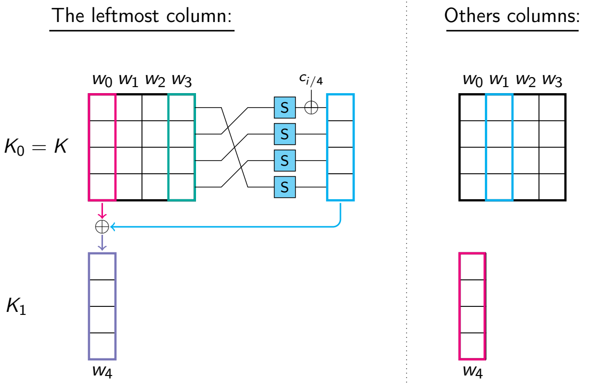

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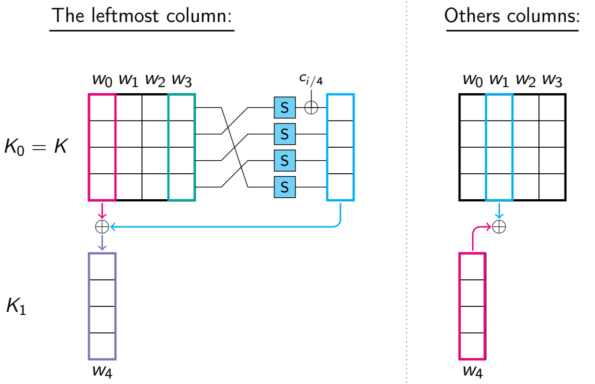

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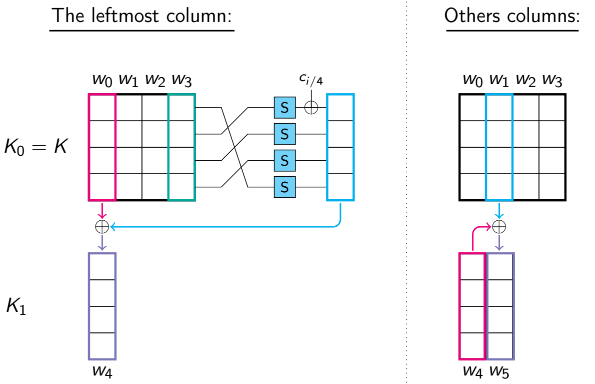

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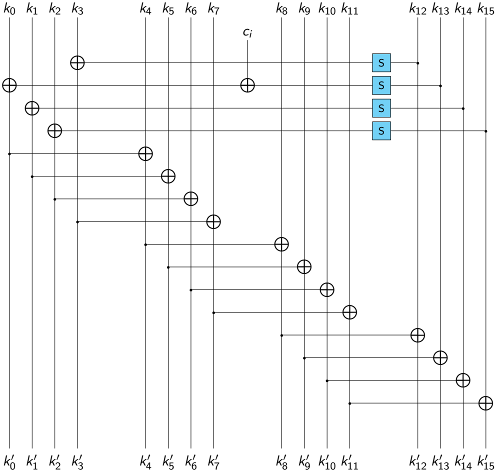
One round of key schedule at byte level



One round of the AES key schedule.

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Difference diffusion

Leander, Minaud and Rønjom ([EC'15]) introduced an algorithm in order to **detect invariant subspaces for a permutation**, *i.e.* a subspace A and an offset u such as:

$$\boxed{F(A + u) = A + F(u)}$$

Let's recall how the generic algorithm works for a permutation $\mathrm{F} : \mathbb{F}_2^n \rightarrow \mathbb{F}_2^n$:

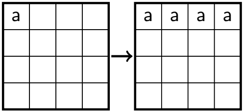
1) Guess an offset $u' \in \mathbb{F}_2^n$ and a one-dimensional subspace A_0.
2) Compute $A_{i+1} = span\{(F(u' + A_i) - F(u')) \cup A_i\}$
3) If the dimension of A_{i+1} equals the dimension of A_i, we found an invariant subspace and exit.
4) Else, we go on step 2.

Difference diffusion

a			

Diffusion of a difference on the first byte after several rounds of key schedule.

Difference diffusion



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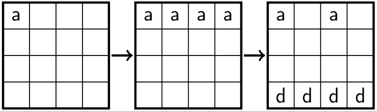

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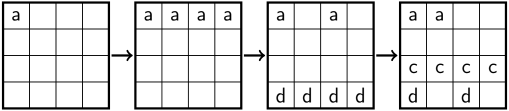

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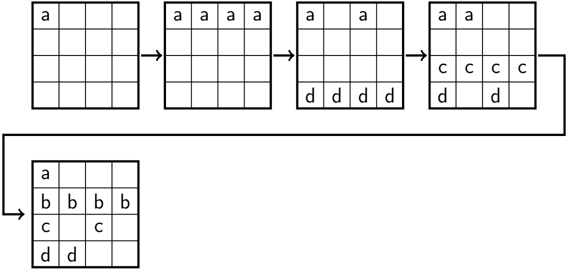

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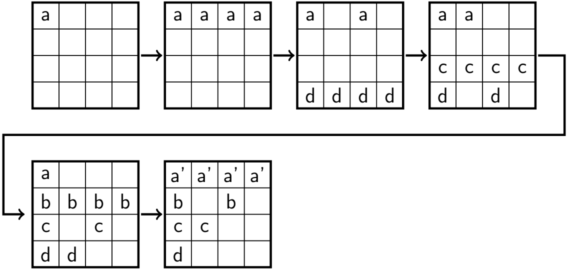

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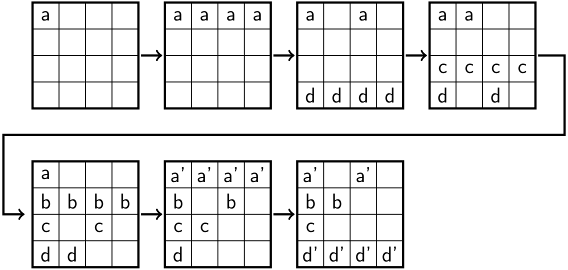

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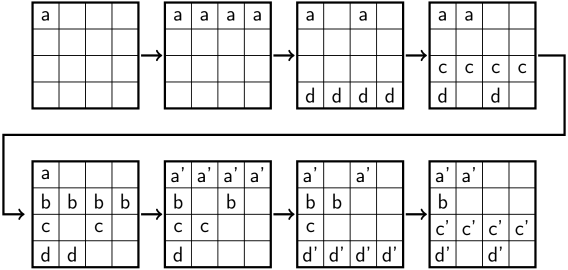

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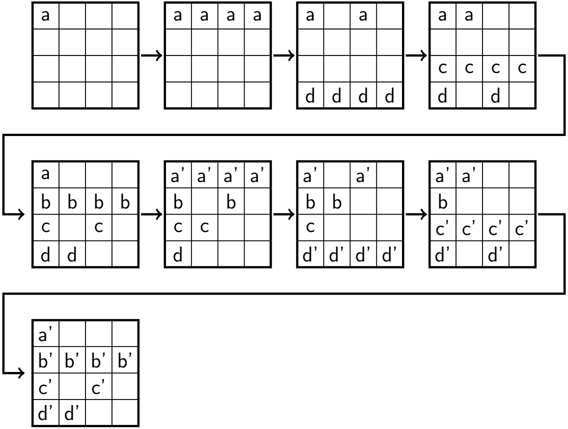

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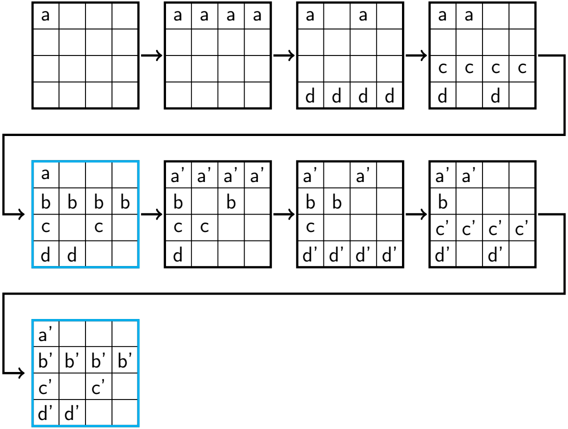

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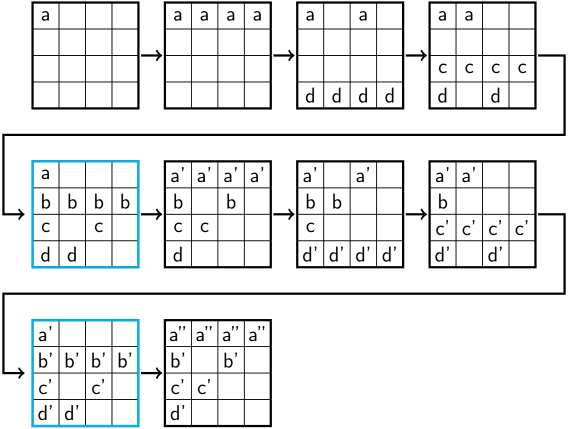

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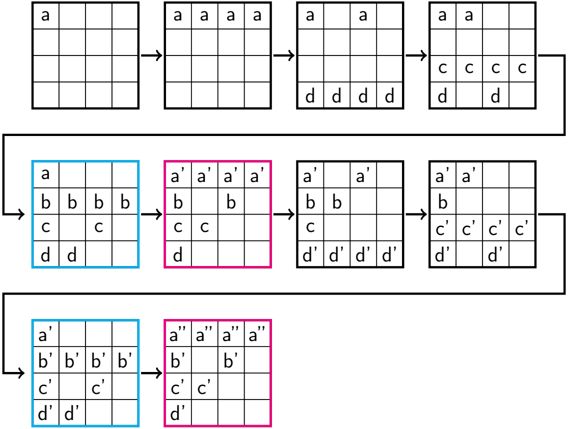

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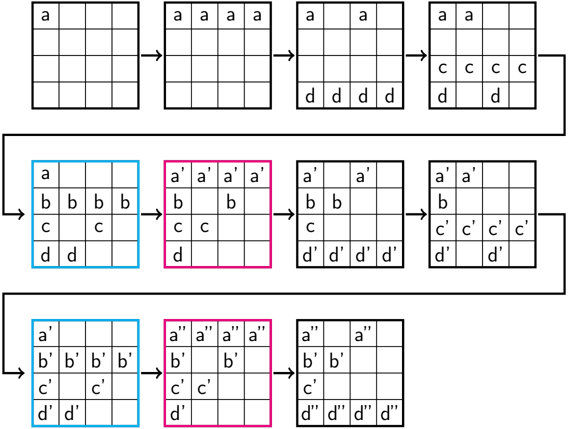

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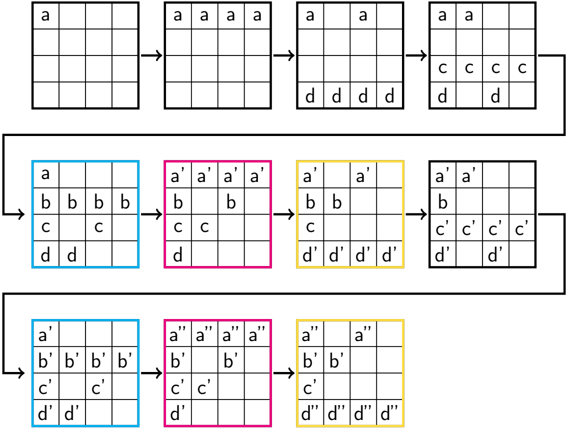

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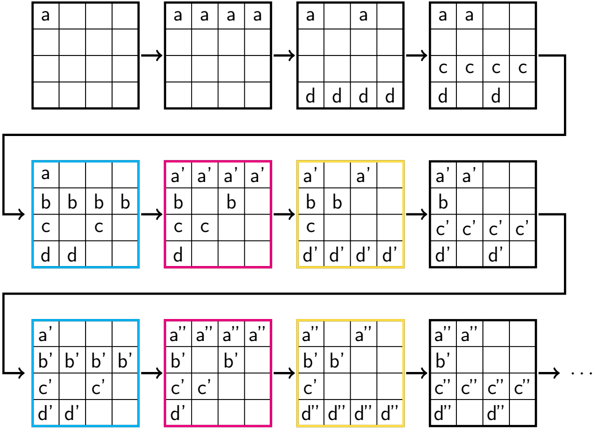

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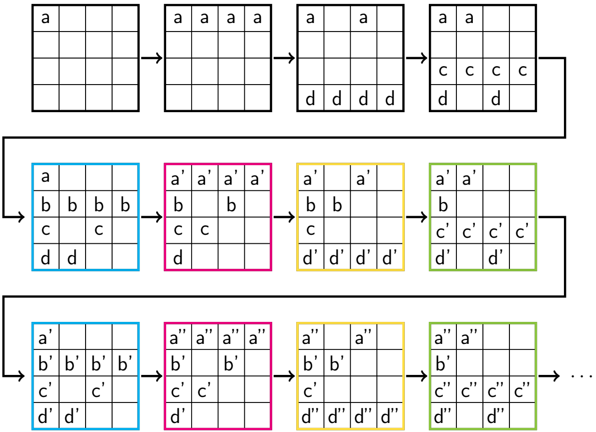

Diffusion of a difference on the first byte after several rounds of key schedule.

Difference diffusion

We obtain **4 invariant affine subspaces** whose linear parts are:

$$E_0 = \{(a, b, c, d, 0, b, 0, d, a, 0, 0, d, 0, 0, 0, d) \text{ with } a, b, c, d \in \mathbb{F}_{2^8}\}$$
$$E_1 = \{(a, b, c, d, a, 0, c, 0, 0, 0, c, d, 0, 0, c, 0) \text{ with } a, b, c, d \in \mathbb{F}_{2^8}\}$$
$$E_2 = \{(a, b, c, d, 0, b, 0, d, 0, b, c, 0, 0, b, 0, 0) \text{ with } a, b, c, d \in \mathbb{F}_{2^8}\}$$
$$E_3 = \{(a, b, c, d, a, 0, c, 0, a, b, 0, 0, a, 0, 0, 0) \text{ with } a, b, c, d \in \mathbb{F}_{2^8}\}$$

$$\boxed{\forall u \in (\mathbb{F}_{2^8})^{16}, R(E_i + u) = E_{i+1} + R(u)}$$

The full space is the direct sum of those four vector spaces:

$$(\mathbb{F}_{2^8})^{16} = E_0 \oplus E_1 \oplus E_2 \oplus E_3$$

New representation of the AES Key Schedule

To describe a representation that makes the **4 subspaces** appear more clearly, we will perform a **linear transformation** $\mathbf{A} = \mathbf{C_0^{-1}}$, which corresponds to a base change:

$$
\begin{array}{rlll}
s_0 = k_{15} & s_1 = k_{14} \oplus k_{10} \oplus k_6 \oplus k_2 & s_2 = k_{13} \oplus k_5 & s_3 = k_{12} \oplus k_8 \\
s_4 = k_{14} & s_5 = k_{13} \oplus k_9 \oplus k_5 \oplus k_1 & s_6 = k_{12} \oplus k_4 & s_7 = k_{15} \oplus k_{11} \\
s_8 = k_{13} & s_9 = k_{12} \oplus k_8 \oplus k_4 \oplus k_0 & s_{10} = k_{15} \oplus k_7 & s_{11} = k_{14} \oplus k_{10} \\
s_{12} = k_{12} & s_{13} = k_{15} \oplus k_{11} \oplus k_7 \oplus k_3 & s_{14} = k_{14} \oplus k_6 & s_{15} = k_{13} \oplus k_9
\end{array}
$$

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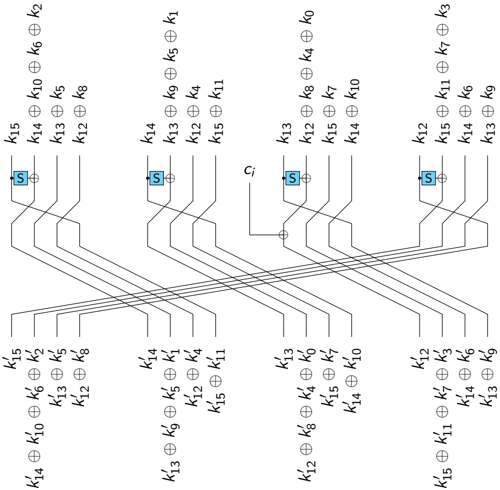
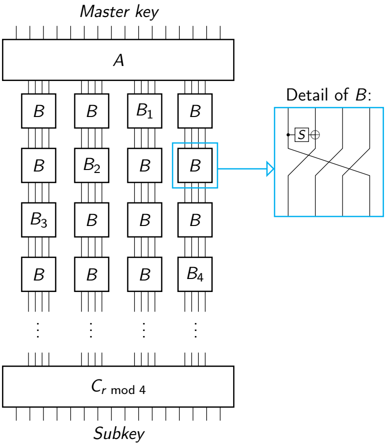


One round of the AES key schedule (alternative representation).

New representation of the AES Key Schedule



r rounds of the key schedule in the new representation.

- B_i is similar to B but the round constant c_i is XORed to the output of the S-box.
- $C_i = A^{-1} \times \mathrm{SR}^i$, with SR the matrix corresponding to rotation of 4 bytes to the right.

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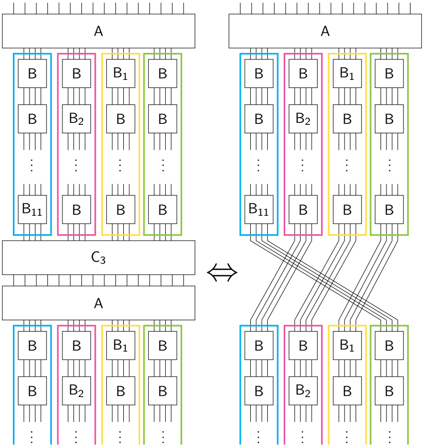
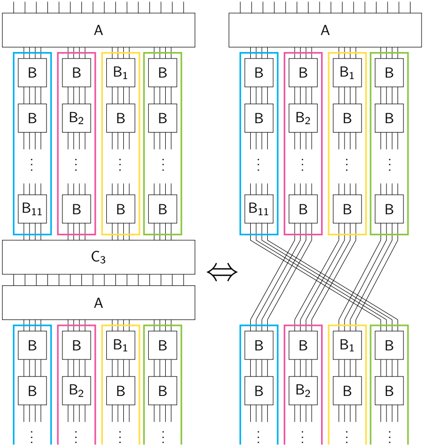
Cycle analysis of 11-round AES key schedule



Two iterations of 11 rounds of the key schedule in the new representation.

Cycle analysis of 11-round AES key schedule



Two iterations of 11 rounds of the key schedule in the new representation.

We define:

$$\boxed{f_1} = B_{11} \circ B \circ B \circ B \circ B_7 \circ B \circ B \circ B \circ B_3 \circ B \circ B$$

$$\boxed{f_2} = B \circ B_{10} \circ B \circ B \circ B \circ B_6 \circ B \circ B \circ B \circ B_2 \circ B$$

$$\boxed{f_3} = B \circ B \circ B_9 \circ B \circ B \circ B \circ B_5 \circ B \circ B \circ B \circ B_1$$

$$\boxed{f_4} = B \circ B \circ B \circ B_8 \circ B \circ B \circ B \circ B_4 \circ B \circ B \circ B$$

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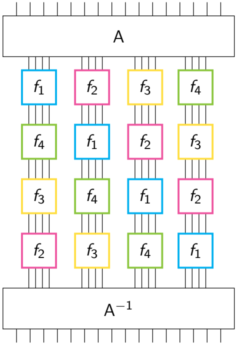

4 iterations of P in the new model.

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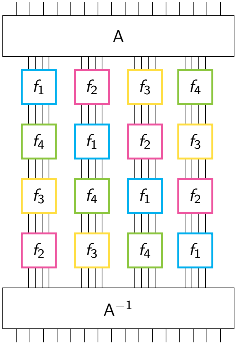

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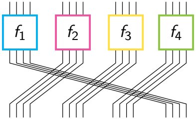

$$\widetilde{P} = A \circ P \circ A^{-1}$$

$$\widetilde{P} : (a, b, c, d) \mapsto (f_2(b), f_3(c), f_4(d), f_1(a))$$

$$\widetilde{P}^4 : (a, b, c, d) \mapsto (\phi_1(a), \phi_2(b), \phi_3(c), \phi_4(d))$$

$$\phi_1(a) = f_2 \circ f_3 \circ f_4 \circ f_1(a)$$

$$\phi_2(b) = f_3 \circ f_4 \circ f_1 \circ f_2(b)$$

$$\phi_3(c) = f_4 \circ f_1 \circ f_2 \circ f_3(c)$$

$$\phi_4(d) = f_1 \circ f_2 \circ f_3 \circ f_4(d)$$

Cycle analysis of 11-round AES key schedule

- If (a, b, c, d) is in a cycle of length ℓ of $\widetilde{P}^4$, we have:

$$\phi_1^\ell(a) = a \qquad \phi_2^\ell(b) = b \qquad \phi_3^\ell(c) = c \qquad \phi_4^\ell(d) = d$$

  In particular, a, b, c and d must be in cycles of ϕ_1, ϕ_2, ϕ_3, ϕ_4 (respectively) of **length dividing** ℓ.

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- Due to the structure of the ϕ_i functions, all of them have the **same cycle structure**:

$$\phi_2 = f_2^{-1} \circ \phi_1 \circ f_2; \qquad \phi_3 = f_3^{-1} \circ \phi_2 \circ f_3; \qquad \phi_4 = f_4^{-1} \circ \phi_3 \circ f_4$$

Cycle analysis of 11-round AES key schedule

Length	# cycles	Proba	Smallest element
3504665256	1	0.82	`00 00 00 01`
255703222	1	0.05	`00 00 00 0b`
219107352	1	0.05	`00 00 00 1d`
174977807	1	0.04	`00 00 00 00`
99678312	1	0.02	`00 00 00 21`
13792740	1	0.003	`00 00 00 75`
8820469	1	$2^{-8,93}$	`00 00 00 24`
7619847	1	$2^{-9,14}$	`00 00 00 c1`
5442633	1	$2^{-9,63}$	`00 00 02 78`
4214934	1	2^{-10}	`00 00 05 77`
459548	1	$2^{-13,2}$	`00 00 38 fe`
444656	1	$2^{-13,24}$	`00 00 0b 68`
14977	1	$2^{-18,13}$	`00 06 82 5c`
14559	1	$2^{-18,18}$	`00 04 fa b1`
5165	1	$2^{-19,67}$	`00 0a d4 4e`
4347	1	$2^{-19,92}$	`00 04 94 3a`
1091	1	$2^{-21.91}$	`00 21 4b 3b`
317	1	$2^{-23,7}$	`00 28 41 36`
27	1	$2^{-27,25}$	`01 3a 0d 0c`
6	1	$2^{-29,42}$	`06 23 25 51`
5	3	$3 \cdot 2^{-29,68}$	`06 1a ea 18`
4	2	$2 \cdot 2^{-30}$	`23 c6 6f 2b`
2	3	$3 \cdot 2^{-31}$	`69 ea 63 75`
1	2	$2 \cdot 2^{-32}$	`7e be d1 92`

Table: Cycle structure of ϕ_1 for 11-round AES-128 key schedule.

Cycle analysis of 11-round AES key schedule

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Table: Cycle structure of ϕ_1 for 11-round AES-128 key schedule.

With probability $0.82^4 \simeq 0.45$, we have a, b, c and d in a cycle of length $\ell = 3504665256$, resulting in:

- $\rightarrow$ a cycle of length ℓ for $\widetilde{P}^4$,
- $\rightarrow$ a cycle of length at most $4\ell = 14018661024$ for $\widetilde{P}$ and P.

Cycle analysis of 11-round AES key schedule

Summary: 45% of keys belong to cycles of length 14018661024 $\approx 2^{33.7}$.

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Summary: 45% of keys belong to cycles of length 14018661024 $\approx 2^{33.7}$.

$\rightarrow$ This explains the observation of Khairallah [ToSC'19].

$\rightarrow$ This contradicts the assumption made in a security proof of mixFeed:

Assumption [NIST LW Workshop]

For any $K \in \{0,1\}^n$ chosen uniformly at random, probability that K has a period at most ℓ is at most $\ell/2^{n/2}$.

Forgery attack against mixFeed [ToSC'19]

The goal of a **forgery attack** is to forge a valid tag T' for a new ciphertext C' using (M, C, T).

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Assuming that Z belongs to a cycle of length ℓ, we have the following attack considering a message M made of m blocks, with $m > \ell$:

1) Encrypt the message M, and obtain the corresponding ciphertext C and tag T.
2) Calculate $S_o[0] = IV$ and $S_i[\ell + 1]$ using M_r and C_r for $r = 1$ and $r = \ell + 1$.
3) Choose M_x and C_x such that $(S_i[\ell + 1], \mathrm{C}_x) = \mathrm{Feed}\ (S_o[0], M_x)$.
4) The T tag will also authenticate the new ciphertext $C' = C_x \| C_{\ell+2} \| \cdots \| C_m$.

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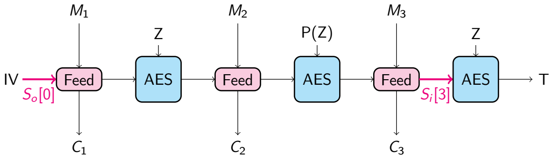

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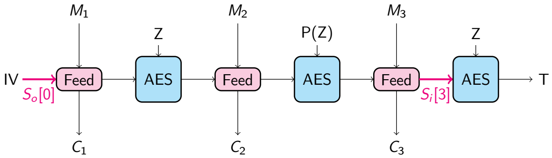

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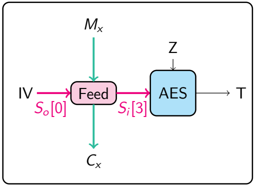

Forgery attack against mixFeed

Summary of the forgery attack:

- $\rightarrow$ Data complexity: a known plaintext of length higher than $2^{37.7}$ bytes
- $\rightarrow$ Memory complexity: negligible
- $\rightarrow$ Time complexity: negligible
- $\rightarrow$ Success rate: 45%

$\Rightarrow$ Verified using the mixFeed reference implementation

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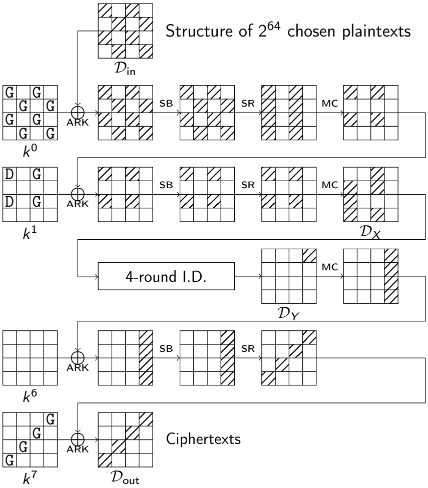
Impossible Differential - AES



7-round impossible differential attack ([MDRM, IC'10]).
Figure adapted from Tikz for Cryptographers [Jean].

The attack is in 2 parts:

(1) find the possible candidates for the bytes marked G.

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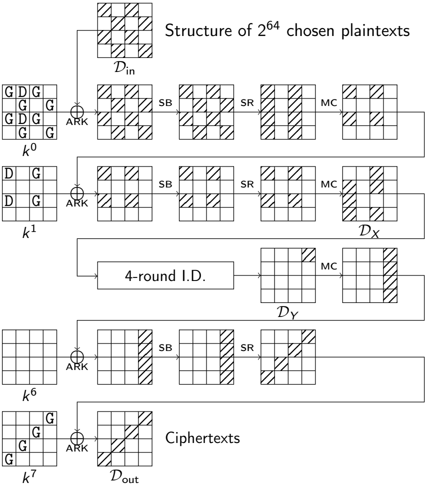

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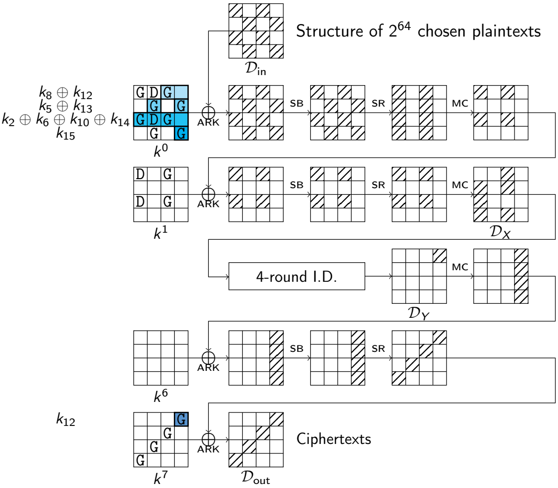

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The attack is in 2 parts:

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We improve (2) by **combining information from k^0 and k^7 more efficiently** thanks to properties related to our new representation.

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For more details:

`https://eprint.iacr.org/2020/1253`