CS5760: Yoyo Tricks with AES

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3. Partitions the plaintext and ciphertext spaces where each partition is closed under exchange operations.
4. Similar to the boomerang attack and works with both Feistel networks and substitution permutation networks (SPNs) that iterate a round function $A \circ S$, where A is an affine transformation and S is a non-linear S-box layer.
5. For analysis, we consider permutations that iterate $L \circ S$, where L is a linear transformation.

Zero Difference Pattern

Suppose $q = 2^k$. Let $\alpha = (\alpha_0, \alpha_1, \ldots, \alpha_{n-1}) \in \mathbb{F}_q^n$, where each $\alpha_i \in \mathbb{F}_q$ is called a *word*.

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Definition 1 (Zero Difference Pattern)

Let $\alpha \in \mathbb{F}_q^n$. Then, the zero difference pattern of α is given by

$$\nu(\alpha) \triangleq (z_0, z_1, \ldots, z_{n-1}) \tag{1}$$

where $z_i = 1$ if $\alpha_i = 0$ or $z_i = 0$ otherwise.

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Observe that $\nu(\alpha) \in \mathbb{F}_2^n$. The complement of $\nu(\alpha)$ is called the *activity pattern*.

Properties of Zero Difference Pattern

Lemma 1

For two states $\alpha, \beta \in \mathbb{F}_q^n$, the zero pattern of their difference is preserved through S. Mathematically,

$$\nu(\alpha \oplus \beta) = \nu(S(\alpha) \oplus S(\beta)). \tag{2}$$

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Proof.

This is evident from the fact that $\alpha_i \oplus \beta_i = 0 \iff s(\alpha_i) \oplus s(\beta_i) = 0$ since s is a permutation. □

Mixture of Pairs

Definition 2

For a vector $v \in \mathbb{F}_2^n$ and a pair of states $\alpha, \beta \in \mathbb{F}_q^n$ define $\rho^v(\alpha, \beta) \in \mathbb{F}_q^n$ where

$$\rho^v(\alpha, \beta)_i \triangleq \alpha_i v_i \oplus \beta_i (v_i \oplus 1) = \begin{cases} \alpha_i & v_i = 1 \\ \beta_i & v_i = 0 \end{cases}. \tag{3}$$

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From the definition it is evident that

$$\rho^v(\alpha, \beta) \oplus \rho^v(\beta, \alpha) = \alpha \oplus \beta. \tag{4}$$

Effect of a Permutation

Lemma 2

Let $\alpha, \beta \in \mathbb{F}_q^n$ *and* $v \in \mathbb{F}_2^n$. *Then,* ρ *commutes with the S-box layer. Mathematically,*

$$\rho^v(S(\alpha), S(\beta)) = S(\rho^v(\alpha, \beta)) \tag{5}$$

and thus

$$S(\alpha) \oplus S(\beta) = S(\rho^v(\alpha, \beta)) \oplus S(\rho^v(\beta, \alpha)). \tag{6}$$

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Proof.

S operates on each word independently and the result follows immediately from definition 2. □

Effect of a Linear Transformation

Lemma 3

For a linear transformation $L(x) = L(x_0, x_1, \ldots, x_{n-1})$ *and for any* $v \in \mathbb{F}_2^n$,

$$L(\alpha) \oplus L(\beta) = L(\rho^v(\alpha, \beta)) \oplus L(\rho^v(\beta, \alpha)) \tag{7}$$

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Proof.

Using (4) and the linearity of L, we have

$$L(\alpha) \oplus L(\beta) = L(\alpha \oplus \beta) = L(\rho^v(\alpha, \beta) \oplus \rho^v(\beta, \alpha)) \tag{8}$$

$$= L(\rho^v(\alpha, \beta)) \oplus L(\rho^v(\beta, \alpha)) \tag{9}$$

□

Combined Effect

1. Using Lemma 2 and Lemma 3, we have

$$L(S(\alpha)) \oplus L(S(\beta)) = L(S(\rho^v(\alpha, \beta))) \oplus L(S(\rho^v(\beta, \alpha))), \tag{10}$$

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2. Switching S and L does not guarantee equality in (10).
3. Zero difference pattern does not change when L or S is applied to any pair $\alpha' = \rho^v(\alpha,\beta)$ and $\beta' = \rho^v(\beta,\alpha)$. Thus,

$$\nu(S(L(\alpha)) \oplus S(L(\beta))) = \nu(S(L(\rho^v(\alpha,\beta))) \oplus S(L(\rho^v(\beta,\alpha)))). \tag{11}$$

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4. Although equality may not hold, differences are zero in exactly the same positions when $S \circ L$ is applied.

Summary Theorem

Theorem 1

Let $\alpha, \beta \in \mathbb{F}_q^n$ *and* $\alpha' = \rho^v(\alpha, \beta), \beta' = \rho^v(\beta, \alpha)$. *Then,*

$$\nu(S \circ L \circ S(\alpha) \oplus S \circ L \circ S(\beta)) = \nu(S \circ L \circ S(\alpha') \oplus S \circ L \circ S(\beta')). \quad (12)$$

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Proof.

The proof follows from the following observations.

1. Lemma 2 gives $S(\alpha) \oplus S(\beta) = S(\alpha') \oplus S(\beta')$.
2. The linearity of L gives $L(S(\alpha)) \oplus L(S(\beta)) = L(S(\alpha')) \oplus L(S(\beta'))$.
3. Finally, Lemma 1 gives (12).

□

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3. Fix a pair of plaintexts p^0, p^1 with a paritcular zero difference pattern $\nu(p^0 \oplus p^1)$.
4. From the corresponding ciphertexts c^0, c^1, construct another pair of new ciphertexts c'^0, c'^1 such that their decrypted plaintexts p'^0, p'^1 also have the same zero difference pattern. This follows directly from Theorem 1 and holds with probability 1.

Summary Theorem

Theorem 2 (Generic Yoyo Game for Two SP-Rounds)

Let $p^0 \oplus p^1 \in \mathbb{F}_q^n$, $c^0 = G_2(p^0)$ and $c^1 = G_2(p^1)$. Then for any $v \in bF_2^n$, let $c'^0 = \rho^v(c^0, c^1)$ and $c'^1 = \rho^v(c^1, c^0)$. Then,

$$\nu(G_2^{-1}(c'^0) \oplus G_2^{-1}(c'^1)) = \nu(p'^0 \oplus p'^1) = \nu(p^0 \oplus p^1). \tag{13}$$

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$$\nu(G_2^{-1}(c'^0) \oplus G_2^{-1}(c'^1)) = \nu(p'^0 \oplus p'^1) = \nu(p^0 \oplus p^1). \tag{13}$$

Proof.

Since S^{-1} is also a permutation and L^{-1} is a linear transformation, we invoke Theorem 1 on $G_2^{-1} = S^{-1} \circ L^{-1} \circ S^{-1}$ to obtain (13). $\square$

Distiguisher for Two SP-Rounds

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1. Theorem 2 gives us a straightforward distinguisher for two generic SP-rounds requiring two plaintexts and two adaptively chosen ciphertexts.
2. A random permutation would not give back a pair of decrypted plaintexts that still have the same zero difference pattern with very high probability.
3. One can also generate two ciphertexts and then observe the ciphertexts of the adaptively chosen plaintexts.

Analysis of Three Generic SP-Rounds

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2. For two states α and β, using Theorem 2, it follows that

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3. Since G_2 and G_2^{-1} have identical forms, we have

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4. Finally, from Lemma 2, zero difference patterns are preserved through an S-box layer.

Summary Theorem

Theorem 3 (Generic Yoyo Game for Three SP-Rounds)

Let $G_3 = S \circ L \circ S \circ L \circ S$. *If* $p^0, p^1 \in \mathbb{F}_q^n$ *and* $c^0 = G_3(p^0)$, $c^1 = G_3(p^1)$, *then*

$$\nu(G_2(\rho^{v_1}(p^0, p^1)) \oplus G_2(\rho^{v_1}(p^1, p^0))) = \nu(G_2^{-1}(\rho^{v_2}(c^0, c^1)) \oplus G_2^{-1}(\rho^{v_2}(c^1, c^0))) \quad (16)$$

for any $v_1, v_2 \in \mathbb{F}_2^n$.

Summary Theorem

Theorem 3 (Generic Yoyo Game for Three SP-Rounds)

Moreover, for any $z \in \mathbb{F}_2^n$, *define*

$$R_P(z) \triangleq \{(p^0, p^1) \mid \nu(G_2(p^0) \oplus G_2(p^1)) = z\} \tag{16}$$

$$R_C(z) \triangleq \{(c^0, c^1) \mid \nu(G_2^{-1}(c^0) \oplus G_2^{-1}(c^1)) = z\} \tag{17}$$

Then, for any $(p^0, p^1) \in R_P(z)$,

$$(G_3(\rho^v(p^0, p^1)), G_3(\rho^v(p^1, p^0))) \in R_C(z), \tag{18}$$

and for any $(c^0, c^1) \in R_C(z)$,

$$(G_3^{-1}(\rho^v(c^0, c^1)), G_3^{-1}(\rho^v(c^1, c^0))) \in R_C(z). \tag{19}$$

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3. The probability that a random pair of plaintexts has a sum with nonzero difference pattern containing exactly m zeros is $\binom{n}{m}\frac{(q-1)^m}{q^n}$ where $q = 2^k$.
4. Thus, we need to test approximately the inverse of that number of pairs to find one correct pair.

Distinguisher for Three Generic SP-Rounds

1. Detecting a correct pair is more involved. Suppose $(p_1, p_2) \in R_P(z)$ and let the respective ciphertexts be (c_1, c_2). Let A be the affine layer in an SASAS construction.

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2. Assume that $S^{-1}(c^0) = x \oplus z$ and $S^{-1}(c^1) = y \oplus z$, where $A^{-1}(x), A^{-1}(y)$ and $A^{-1}(z)$ are non-zero only in the positions where z is zero.

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3. It follows that x and y belong to a linear subspace U of dimension $n - m$ while z belongs to the complementary linear subspace V of dimension m such that $U \oplus V = \mathbb{F}_q^n$.
4. We need to investigate whether $c^0 \oplus c^1 = S(x \oplus z) \oplus S(y \oplus z)$ has some distinguishing properties.

Round Function of AES

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2. Since differences are used, strip AK operations. SR and SB commute.
3. Two rounds of AES can be written as

$$R^{2\prime} = MC \circ SR \circ (SB \circ MC \circ SB) \circ SR \tag{20}$$

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   where $S = SB \circ MC \circ SB$ can be thought of as four parallel 32-bit super S-boxes.
4. The initial SR has no effect, thus $R^2 = MC \circ SR \circ S$.

Representing AES as Generic SP-rounds

1. Considering $S = SB \circ MC \circ SB$ and $L = SR \circ MC \circ SR$, four rounds of AES can be represented using (20) as $R^{4'} = MC \circ SR \circ S \circ L \circ S \circ SR$ which ends up becoming $R^4 = S \circ L \circ S$.

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   - 5 active super S-boxes due to the linear layer.
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2. This also shows that a lower bound on the number of active S boxes over four rounds is 25.
   - 5 active super S-boxes due to the linear layer.
   - At least 5 active S boxes inside a super S-box due to MixColumns.
3. Similarly, six rounds of AES can be written as

$$R^6 = S \circ L \circ S \circ L \circ S. \tag{21}$$

Definitions of Q, Q'

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2. Adding another round at the end of (20), three rounds of AES can be written as $Q \circ S$.

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2. Adding another round at the end of (20), three rounds of AES can be written as $Q \circ S$.
3. Similarly, five rounds of AES can be written as $S \circ L \circ S \circ Q'$.

Properties of Q, Q'

1. For a binary vector $z \in \mathbb{F}_4^2$ of weight t, let V_z denote the subspace of $q^{4\cdot(4-t)}$ states $x = (x_0, x_1, x_2, x_3)$ where $x_i \in \mathbb{F}_q^4$ if $z_i = 0$ or $x_i = 0$ otherwise.

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2. For any state $a = (a_0, a_1, a_2, a_3)$, let

$$T_{z,a} \triangleq \{Q(a \oplus x) \mid x \in V_z\}. \tag{22}$$

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3. Note that $T_{z,a}$ depends on keyed functions. Let H_i denote the image of the i-th word in $SR(a \oplus x)$ for $x \in V_z$. Notice that $|H_i| = q^{4-t}$.

Properties of Q, Q'

1. For a binary vector $z \in \mathbb{F}_4^2$ of weight t, let V_z denote the subspace of $q^{4\cdot(4-t)}$ states $x = (x_0, x_1, x_2, x_3)$ where $x_i \in \mathbb{F}_q^4$ if $z_i = 0$ or $x_i = 0$ otherwise.
2. For any state $a = (a_0, a_1, a_2, a_3)$, let

$$T_{z,a} \triangleq \{Q(a \oplus x) \mid x \in V_z\}. \tag{22}$$

3. Note that $T_{z,a}$ depends on keyed functions. Let H_i denote the image of the i-th word in $SR(a \oplus x)$ for $x \in V_z$. Notice that $|H_i| = q^{4-t}$.
4. Define

$$T_i^{z,a} \triangleq SB \circ MC(H_i). \tag{23}$$

Since SB and MC operate on each word individually, we obtain the following.

Properties of Q, Q'

Lemma 4

The set $T_{z,a}$ satisfies

$$T_{z,a} = T_0^{z,a} \times T_1^{z,a} \times T_2^{z,a} \times T_3^{z,a} \tag{24}$$

where $\left|T_i^{z,a}\right| = q^{4-hw(z)}$, with $hw(z)$ denoting the Hamming weight of z.

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Proof.

Each word of $Q(a \oplus x)$ contributes one byte to each word after SR. If $4 - t$ words are nonzero, it follows that each word after SR can take exactly q^{4-t} values. Thus, $T_i^{z,a} = SB \circ MC(H_i)$. $\square$

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A similar property can be derived for Q' and its inverse as well.

The SimpleSWAP Algorithm

Algorithm 1 is a primitive used to perform the yoyo itself.

Algorithm 1 Swaps the first word where texts are different and returns one word.

---

function $\textsc{SimpleSWAP}(x^0, x^1)$ $\quad \triangleright\ x^0 \neq x^1$
  $x'^0 \leftarrow x'^1$
  for i from 0 to 3 **do**
    if $x^0_i \neq x^1_i$ **then**
      $x'^0_i \leftarrow x'^1_i$
      return x'^0

Distinguisher for Three Rounds of AES

1. Consider plaintexts p^0, p^1 such that $z = \nu(p^0 \oplus p^1)$ and $t = hw(z)$.

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4. In paritcular,

$$T'_{z,a} = \{c_0^0, c_0^1\} \times \{c_1^0, c_1^1\} \times \{c_2^0, c_2^1\} \times \times \{c_3^0, c_3^1\} \subset T_{z,a}. \tag{25}$$

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5. Any other $c' \neq c^0, c^1 \in T'_{z,a}$ satisfies $\nu(Q^{-1}(c') \oplus S(p^0)) = \nu(Q^{-1}(c') \oplus S(p^1)) = \nu(S(p^0) \oplus S(p^1))$.

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where the size of $T'_{z,a}$ is at most 2^4 and $\{c_i^0, c_i^1\} \subset T_i^{z,a}$.
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6. In particular, $\nu(R^{-3}(c') \oplus p^0) = \nu(R^{-3}(c') \oplus p^1) = \nu(p^0 \oplus p^1)$.
7. With a random permutation, the chosen ciphertext c' would satisfy this condition with probability 2^{-96}.

Distinguisher for Three Rounds of AES

Algorithm 2 Distinguisher for Three Rounds of AES

Require: Plaintexts p^0, p^1 with $hw(\nu(p^0 \oplus p^1)) = 3$
Ensure: 1 for AES, -1 otherwise

1: $c^0 \leftarrow enc_k(p^0, 3)$, $c^1 \leftarrow enc_k(p^1, 3)$
2: $c' \leftarrow \textsc{SimpleSWAP}(c^0, c^1)$
3: $p' \leftarrow dec_k(c', 3)$
4: **if** $\nu(p^0 \oplus p^1) = \nu(p' \oplus p^1)$ **then**
5:     **return** 1
6: **else**
7:     **return** -1

Data complexity: two plaintexts and one adaptively chosen ciphertext.

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2. Theorem 2 is invoked to create the distinguisher.
3. Again, the new ciphertexts are created by simply exchanging words between the two obtined ciphertexts, as shown in Algorithm 3.

Distinguisher for Four Rounds of AES

Algorithm 3 Distinguisher for Four Rounds of AES

Require: Plaintexts p^0, p^1 with $hw(\nu(p^0 \oplus p^1)) = 3$
Ensure: 1 for AES, -1 otherwise

1: $c^0 \leftarrow enc_k(p^0, 4)$, $c^1 \leftarrow enc_k(p^1, 4)$
2: $c'^0 \leftarrow \text{SIMPLESWAP}(c^0, c^1)$, $c'^1 \leftarrow \text{SIMPLESWAP}(c^1, c^0)$
3: $p'^0 \leftarrow dec_k(c'^0, 4)$, $p'^1 \leftarrow dec_k(c'^1, 4)$
4: **if** $\nu(p^0 \oplus p^1) = \nu(p'^0 \oplus p'^1)$ **then**
5:     **return** 1
6: **else**
7:     **return** -1

Data complexity: two plaintexts and two adaptively chosen ciphertexts.

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1. If the difference between two plaintexts after Q' is zero in t words, we can apply the yoyo game and get new pairs that are zero in exactly the same words after Q' and reside in the same sets by Lemma 4.

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2. In paritcular, if a pair of plaintexts p^0, p^1 are encrypted through Q' to a pair of intermediate states with zero difference in 3 out of 4 words, then they have probability q^{-1} of having the same value in a particular word, since $\left|T_i^{z,a}\right| = q^{4-3} = q$ by Lemma 4.

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3. A property of the MixColumns matrix can be exploited to get a tighter bound, which is stated below.

Lemma 5

Let M denote a 4×4 MixColumns matrix and $x \in \mathbb{F}_q^4$. If t bytes in x are zero, then $x \cdot M$ or $x \cdot M^{-1}$ cannot contain $4 - t$ or more zeros.

Summary Theorem

Theorem 4

Let a and b denote two states where $\nu(Q'(a) \oplus Q'(b))$ has weight t. Then, the probability that any $4 - t$ bytes are simultaneously zero in a word in the difference $a \oplus b$ is q^{t-4}. When this happens, all bytes in the difference are zero.

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Proof.

From Lemma 4, words in same positions are drawn from $T_i^{z,a}$ with size q^{4-t}, thus they are equal with probability q^{t-4}. Since t words are zero in $Q'(a) \oplus Q'(b)$, each word of $SR^{-1}(Q'(a)) \oplus SR^{-1}(Q'(b))$ has t zero bytes. From Lemma 5, $4 - t$ bytes cannot be zero in each word after MC^{-1}. This is preserved through SB^{-1} and XOR with the round key. □

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4. This would imply $Q'(p^0) \oplus Q'(p^1)$ has t zero words.
5. Playing the yoyo game on R^4 will return at most 7 new plaintext pairs which have the same zero difference pattern after one round and obey Theorem 4.

Attack Analysis

1. The probability that a pair (p^0, p^1) with a zero difference pattern of weight 3 has a zero difference pattern of weight t when encrypted through Q' is (where $q = 2^8$)

$$p_b(t) = \binom{4}{t} q^{-t}. \tag{26}$$

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2. We require $p_b(t)^{-1}$ pairs to get one such pair. To distinguish it, notice that for a random pair of plaintexts, the probability that $4 - t$ bytes are zero simultaneously in any of the 4 words is approximately

$$4p_b(4-t) = 4 \cdot \binom{4}{t} \cdot q^{t-4} \tag{27}$$

while for a correct pair it is $4 \cdot q^{t-4}$.

Data Complexity

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3. For $t = 2$, the data complexity is minimum at approximately $2^{25.8}$. The overall distinguisher is shown in section 4.

Distinguisher for Five Rounds of AES I

Ensure: 1 for AES, -1 otherwise

$cnt1 \leftarrow 0$.
while $cnt1 < 2^{13.4}$ **do**
  $cnt1 \leftarrow cnt1 + 1$.
  $p^0, p^1 \leftarrow$ generate random pair with $hw(\nu(p^0 \oplus p^1)) = 3$.
  $cnt2 \leftarrow 0$, $WrongPair \leftarrow False$.
  while $cnt2 < 2^{11.4}$ & $WrongPair = False$ **do**
    $cnt2 \leftarrow cnt2 + 1$.
    $c^0 \leftarrow enc_k(p^0, 5)$, $c^1 \leftarrow enc_k(p^1, 5)$.
    $c'^0 \leftarrow \textsc{SimpleSWAP}(c^0, c^1)$, $c'^1 \leftarrow \textsc{SimpleSWAP}(c^1, c^0)$.
    $p'^0 \leftarrow dec_k(c'^0, 5)$, $p'^1 \leftarrow dec_k(c'^1, 5)$.
    for i from 0 to 3 **do**

Distinguisher for Five Rounds of AES II

```
            if hw(ν(p_i)) ≥ 2 then
                WrongPair = True
        p'^0 ← SimpleSWAP(p^0, p^1), p'^1 ← SimpleSWAP(p^1, p^0).
    if WrongPair = False then
        return 1        ▷ Did not find difference with two or more zeros.
return -1
```

Five Round Key Recovery Yoyo on AES

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$$M = \begin{pmatrix} \alpha & \alpha \oplus 1 & 1 & 1 \\ 1 & \alpha & \alpha \oplus 1 & 1 \\ 1 & 1 & \alpha & \alpha \oplus 1 \\ \alpha \oplus 1 & 1 & 1 & \alpha \end{pmatrix}. \tag{29}$$

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3. Pick two plaintexts p^0 and p^1 where the first words are given by $p_0^0 = (0, i, 0, 0)$ and $p_0^1 = (z, z \oplus i, 0, 0)$ where $z \in \mathbb{F}_q \setminus \{0\}$ and the three other words are equal. Let $k_0 = (k_{0,0}, k_{0,1}, k_{0,2}, k_{0,3})$ denote key bytes XORed with the first word of the plaintext.

Five Round Key Recovery Yoyo on AES

1. The difference between the first words after partial encryption of the two plaintexts $MC \circ SB \circ AK$ becomes

$$\alpha b_0 \oplus (\alpha \oplus 1) b_1 = y_0 \tag{30}$$

$$b_0 \oplus \alpha b_1 = y_1 \tag{31}$$

$$b_0 \oplus b_1 = y_2 \tag{32}$$

$$(\alpha \oplus 1) b_0 \oplus b_1 = y_3 \tag{33}$$

where $b_0 = s(k_{0,0}) \oplus s(z \oplus k_{0,0})$ and $b_1 = s(k_{0,1} \oplus i) \oplus s(k_{0,1} \oplus z \oplus i)$.

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2. (32) can be written as

$$s(k_{0,0}) \oplus s(k_{0,0} \oplus z) \oplus s(k_{0,1} \oplus i) \oplus s(k_{0,1} \oplus z \oplus i) = y_2. \tag{34}$$

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2. (32) can be written as
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3. Note that $y_2 = 0$ for $i \in \{k_{0,0} \oplus k_{0,1}, k_{0,0} \oplus k_{0,1} \oplus z\}$. Hence, there will be at least two values of $i \in \mathbb{F}_q$ for which $y_2 = 0$.

Five Round Key Recovery Yoyo on AES

5. Define $B = M \circ s^4$ to be the action of $MC \circ SB$ on one column, where s^4 is the concatenation of four S-boxes in parallel.

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6. Prepare a set $\mathcal{P}$ of plaintexts p^0 and p^1 where $p_0^0 = (0, i, 0, 0)$ and $p_0^1 = (z, z \oplus i, 0, 0)$. Let c^0, c^1 be the respective ciphertexts.

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7. Pick 5 new ciphertext pairs $(c'^0, c'^1) = (\rho^v(c^0, c^1), \rho^v(c^1, c^0))$ and let p'^0, p'^1 be the respective plaintexts.

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8. A correct pair will satisfy

$$B(p_0'^0 \oplus k_0) \oplus B(p_0'^1 \oplus k_0) = (z_0, z_1, 0, z_3). \tag{35}$$

Five Round Key Recovery Yoyo on AES

9. The adversary can now test the remaining 2^{24} candidate keys and find whether the third byte of the first word is zero for all 5 pairs of plaintexts, where $k_{0,0} \oplus k_{0,1} \in \{i, i \oplus z\}$ for known i and z.

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10. This holds for all 5 pairs at random with probability $2^{-8 \cdot 5} = 2^{-40}$.

Five Round Key Recovery Yoyo on AES

9. The adversary can now test the remaining 2^{24} candidate keys and find whether the third byte of the first word is zero for all 5 pairs of plaintexts, where $k_{0,0} \oplus k_{0,1} \in \{i, i \oplus z\}$ for known i and z.
10. This holds for all 5 pairs at random with probability $2^{-8 \cdot 5} = 2^{-40}$.
11. A false positive might occur with probability 2^{-16} when testing 2^{24} keys. This probability can be reduced by testing with additional pairs when the test succeeds on the first five pairs, which is rare.

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2. For the computational complexity, we need to test 2^{24} keys for each set of plaintexts as we only need to set $k_{0,1} = k_{0,0} \oplus i$, since $k_{0,0}, i \in \mathbb{F}_q$. For each key, we will have $2 \cdot 4$ S-box lookups for 5 pairs to check (35), giving a total complexity of $2^{24} \cdot 2 \cdot 4 \cdot 5 \cdot 2^8 = 2^{37.3}$.

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3. This cooresponds to approximately2^{31} 5-rounds of AES (assuming 80 S-box lookups per encryption).

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3. However, this pair is useless in recovering the other subkeys since the last three words are equal.
4. The yoyo can be used from this initial pair to generate pairs (p'^0, p'^1) that are with high probability different in the last three words and whose difference after $SR \circ MC \circ SB \circ AK$ is non-zero only in the first word.

Extracting the Full Subkey

6. To attack k_1, notice that each of the m pairs returned by the yoyo satisfy

$$B(p_1'^0 \oplus k_1) \oplus B(p_1'^1 \oplus k_1) = (0, w, 0, 0) \tag{37}$$

for some $w \in \mathbb{F}_q$ and fixed k_1. This is because the i-th byte of the i-th word can be nonzero before SR.

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7. Notice that (37) can be written as
$$M^{-1}(0, w, 0, 0) = w \cdot M_2^{-1} = s^4(p_1'^0 \oplus k_1) \oplus s^4(p_1'^1 \oplus k_1). \tag{38}$$
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9. Similarly, k_2 and k_3 can be found using analogous relationships with columns of M^{-1}.

Recovering all Round Subkeys

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2. Since the initial pair is useless, 5 pairs are used to recover the full key.

Key Recovery Algorithm for Five Rounds of AES I

Ensure: Secret key k_0

for i from 0 to $2^8 - 1$ **do**

  $p^0 \leftarrow 0,\ p^1 \leftarrow 0$

  $p^0_0 \leftarrow (0, i, 0, 0),\ p^1_0 \leftarrow (1, 1 \oplus i, 0, 0)$

  $\mathcal{S} \leftarrow \{(p^0, p^1)\}$

  while $|\mathcal{S}| < 5$ **do**

    $c^0 \leftarrow enc_k(p^0, 5),\ c^1 \leftarrow enc_k(p^1, 5)$

    $c'^0 \leftarrow \textsc{SimpleSWAP}(c^0, c^1),\ c'^1 \leftarrow \textsc{SimpleSWAP}(c^1, c^0)$

    $p'^0 \leftarrow dec_k(c'^0, 5),\ p'^1 \leftarrow dec_k(c'^1, 5)$

    $p^0 \leftarrow \textsc{SimpleSWAP}(p'^0, p'^1),\ p^1 \leftarrow \textsc{SimpleSWAP}(p'^1, p'^0)$

    $\mathcal{S} \leftarrow \mathcal{S} \cup \{(p^0, p^1)\}$

  for all 2^{24} key candidates k_0 **do**

Key Recovery Algorithm for Five Rounds of AES II

```
        for all (p^0, p^1) ∈ S do
            if l_3(s^4(p^0_0 ⊕ k_0) ⊕ s^4(p^1_0 ⊕ k_0)) ≠ 0 then
                Break and jump to next key
        return k_0
```