[13] National Bureau of Standards, *DES Modes of Operation*, U.S. Department of Commerce, FIPS pub. 81, December 1980.

[14] Paul C. van Oorschot, Michael J. Wiener, *A Known Plaintext Attack on Two-Key Triple Encryption*, Lecture Notes in Computer Science, Advances in Cryptology, proceedings of EUROCRYPT'90, pp. 318–325, 1990.

[15] Bart Preneel, Marnix Nuttin, Vincent Rijmen, Johan Buelens, *Cryptanalysis of the CFB Mode of the DES with a Reduced Number of Rounds*, Lecture Notes in Computer Science, Advances in Cryptology, proceedings of CRYPTO'93, pp. 212–223, 1993.

[16] Akihiro Shimizu, Shoji Miyaguchi, *Fast Data Encryption Algorithm FEAL*, Lecture Notes in Computer Science, Advances in Cryptology, proceedings of EUROCRYPT'87, pp. 267–278, 1987.

[17] Michael J. Wiener, *Efficient DES Key Search*, technical report TR-244, School of Computer Science, Carleton University, Ottawa, Canada, May 1994. Presented at the Rump session of CRYPTO'93, August 1993.

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References

[1] Eli Biham, *On Matsui's Linear Cryptanalysis*, Lecture Notes in Computer Science, Advances in Cryptology, proceedings of EUROCRYPT'94, to appear.

[2] Eli Biham, Alex Biryukov, *An Improvement of Davies' Attack on DES*, Lecture Notes in Computer Science, Advances in Cryptology, proceedings of EUROCRYPT'94, to appear.

[3] Eli Biham, Adi Shamir, *Differential Cryptanalysis of the Data Encryption Standard*, Springer-Verlag, 1993.

[4] Eli Biham, Adi Shamir, *Differential Cryptanalysis of the full 16-round DES*, Lecture Notes in Computer Science, Advances in Cryptology, proceedings of CRYPTO'92, pp. 487–496, 1992.

[5] D. W. Davies, *Investigation of a Potential Weakness in the DES Algorithm*, 1987, private communication.

[6] Carl Ellison, private communications, 1993.

[7] Shimon Even, Oded Goldreich, *On the Power of Cascade Ciphers*, ACM Transactions on Computer Systems, Vol. 3, NO. 2, pp. 108–116, May 1985.

[8] Burt Kaliski, *Triple-DES: A Brief Report*, RSA laboratories, private communication, October 29, 1993.

[9] Mitsuru Matsui, *Linear Cryptanalysis Method for DES Cipher*, Lecture Notes in Computer Science, Advances in Cryptology, proceedings of EUROCRYPT'93, pp. 386–397, 1993.

[10] Ueli M. Maurer, James L. Massey, *Cascade Ciphers: The Importance of Being First*, Journal of Cryptology, Vol. 6, No. 1, pp. 55–61, 1993.

[11] Shoji Miyaguchi, Akira Shiraishi, Akihiro Shimizu, *Fast Data Encryption Algorithm FEAL-8*, Review of electrical communications laboratories, Vol. 36, No. 4, pp. 433–437, 1988.

[12] National Bureau of Standards, *Data Encryption Standard*, U.S. Department of Commerce, FIPS pub. 46, January 1977.

Mode	Cryptanalysis Using Technique					
	A	B	C	D	E	F
ECB|CBC|CBC	2^{47}		2^{60}			2^{58}
CBC|ECB|CBC		2^{61}	2^{60}			2^{58}
CBC|CBC|ECB		2^{61}	2^{60}		2^{56}	
CBC|CBC|CBC				2^{66}		2^{58}
CBC|CBC^{-1}|CBC						2^{66}
CBC feedback every round				Few		

Table 1. Summary of the easiest-key (chosen ciphertext) attacks on multiple modes of DES.

Mode	Cryptanalysis Using Technique					
	A	B	C	D	E	F
ECB|CBC|CBC	1000		2^{24}			2^{66}
CBC|ECB|CBC		1000	2^{24}			2^{66}
CBC|CBC|ECB		1000	2^{24}		2^{64}	
CBC|CBC|CBC				2^{17}		2^{66}
CBC|CBC^{-1}|CBC						2^{66}
CBC feedback every round				Few		

Table 2. Summary of the easiest-key (chosen ciphertext) attacks on multiple modes of Feal-8.

We conclude that strong modes of operation should not be based on combining simpler modes, nor use internal feedbacks. We suggest to use single modes, and to incorporate multiple encryption as the underlying cryptosystems of the single modes. Alternatively, whenever we have a multiple mode or any other mode which uses internal feedbacks, it can be strengthened by eliminating the use of the internal feedbacks.

Mode	Complexity E=DES	Complexity E=Feal-8
ECB|CBC|CBC	2^{58}	2^{17}
CBC|ECB|CBC	2^{58}	2^{17}
CBC|CBC|ECB	2^{58}	2^{17}
CBC|CBC|CBC	2^{59}	2^{18}
CBC|CBC^{-1}|CBC	2^{66}	2^{66}
CBC feedback every round	Few	Few

Table 3. Total complexities of the attacks on the multiple modes.

in $(?, H, H, H)$, where $H = C \oplus \mathrm{DES}_{k_3}^{-1}(C)$. H is a pseudo-random function of C (and not a permutation of the values of C). Thus, given 2^{33} random C's, with a high probability two of the C's result with the same H. Therefore, for these two C's, the same value of P_3 is expected. False alarms can result from the first two single CBC modes (due to the same property), and thus the following analysis should be repeated three times on average until K_3 is found.

Given the 2^{33} P_3's resulting from triple CBC decryption of the (C, C, C, C) tuples, we search for pairs of C and C^* for which $P_3 = P_3^*$. For such pairs we assume that both C and C^* satisfy

$$C \oplus \mathrm{DES}_{k_3}^{-1}(C) = C^* \oplus \mathrm{DES}_{k_3}^{-1}(C^*).$$

Then, we exhaustively evaluate this equation for all the 2^{56} possible values of K_3. The equation is satisfied for a fraction of about 2^{-64} of the wrong keys, and thus we can be quite sure that a key satisfying this equation is the right key. (To decrease the false alarm probability, we can select only keys which satisfy the equation using two different pairs of tuples). Note that after we find K_3, the same technique can find K_2 using the same data. Then, K_1 can be found by exhaustive search, differential cryptanalysis or linear cryptanalysis.

A more sophisticated variant of this technique can attack the CBC|CBC^{-1}|CBC (CBC encrypt, CBC decrypt, CBC encrypt) mode with 2^{66} chosen ciphertexts and complexity.

4 Summary

We studied the strength of multiple modes of operation. We showed that in many cases, these modes are weaker than the corresponding multiple ECB mode. In several cases, these modes are not more secure than just one single encryption using the same cryptosystem. For example, a triple CBC mode (doing CBC|CBC|CBC), each encrypts using a single DES and the modes CBC|CBC|ECB, CBC|ECB|CBC and ECB|CBC|CBC are weaker than triple DES, and their strength is comparable to the strength of a single DES. The triple mode CBC|CBC^{-1}|CBC, where CBC^{-1} is CBC decryption, is not much stronger.

Tables 1 and 2 summarize the results obtained for the multiple modes of operation when the underlying cryptosystems are DES and Feal-8 respectively. All the attacks are chosen ciphertext attacks. The complexities quoted are the complexities of finding one key of one of the single modes (i.e., the easiest key to find), in terms of the number of tuples required or the complexity of the analysis (the largest of them). To find the other keys the complexity might be higher. Table 3 summarizes the total complexities of attacking the multiple modes of operation, and finding all their keys. In the full paper we will describe results on multiple modes incorporating additional single modes (such as CFB).

and thus the number of required plaintexts is similar to the number of plaintexts required by a 0R-attack (1R-attack). This technique cannot use linear cryptanalysis.

One could also design modes with many feedbacks, that would seem more secure than modes with a small number of feedbacks. If we would take this suggestion to extreme, we could CBC-feedback every round of the triple-encryption, resulting with 48 feedbacks. This would make the intermediate data during the triple encryption be more dependent on the previous blocks, and would increase the avalanche of the previous blocks. However, as we conclude from the triple CBC mode above, any multiple CBC mode is not more secure that its basic box against 0R-attacks. In this suggestion, the basic box is just one round, which is trivial to break. Thus, this extreme suggestion is also trivial to break. An attack requires only few chosen ciphertexts to find all the subkeys, even if independent keys are used.

3.5 Technique E: Using Exhaustive Search

The best example of this technique analyzes the CBC|CBC|ECB mode. This technique finds the key of the last (ECB) encryption box using exhaustive search.

The attacker chooses one pair of ciphertext tuples (C_0, C_1, C_2) and (C_0^*, C_1, C_2) in which $C_0 \neq C_0^*$. For this pair, $P_2 \oplus P_2^*$ equals the difference of the input of the last encryption box of block 0. Thus, we can exhaustively search all values of K_3 by decrypting C_0 and C_0^* and verifying that the difference of the results equals $P_2 \oplus P_2^*$.

Unlike most of the techniques that we describe, this technique has a known plaintext variant. Given about 2^{65} known plaintexts, the birthday paradox predicts the existence of two tuples (C_0, C_1, C_2) and (C_0^*, C_1^*, C_2^*) in which $C_1 = C_1^*$, $C_2 = C_2^*$. The same technique might be applied on this pair.

3.6 Technique F: The Birthday Technique

This technique has several variants, of which only one is described in this section. All these variants use the birthday paradox to find good samples for cryptanalysis, and they can use differential cryptanalysis, linear cryptanalysis and exhaustive search for finding the key of a single component. The variant we describe in this section cryptanalyzes the last encryption box of the triple CBC mode (or any multiple CBC/ECB mode whose last component is CBC), and it finds the key of the last component by exhaustive search.

This variant requires the attacker to choose 2^{33} ciphertext tuples of the form (C, C, C, C), where C is chosen at random, and to receive the corresponding plaintexts (P_0, P_1, P_2, P_3), of which only the P_3's are actually required.

The CBC decryption of the third single CBC mode of a tuple (C, C, C, C) results

search with complexity about 2^{55}. The other keys of the ECB|CBC|CBC and the CBC|CBC|ECB modes should be found by techniques D or F.

A similar technique can use the improved Davies' attack[5,2], but its complexity is expected to be higher than with linear cryptanalysis.

3.4 Technique D

In technique B we used the single ECB component within the multiple mode to allow a fixed value to be XORed to the input pairs of the ECB component, and thus we could handle the additional mixing of the plaintexts before they are entered to the encryption boxes. Whenever we do not have a single ECB component in our mode, like in the triple CBC mode (CBC|CBC|CBC), we can use another enhancement of the basic technique, that allows to find the keys of the encryption boxes.

For the triple CBC mode, we choose the pairs of four-block tuples (C_0, C_1, C_2, C_3) and (C_0, $C_1 \oplus \Omega_T$, C_2, C_3) (with the difference (0, Ω_T, 0, 0)), with the same C_0, C_1 and C_2 in all the pairs. The various pairs differ only in the values of C_3, while the two members of a single pair differ only in the value of C_1. Thus, the differences are developed during decryption to (–, A, Ω_T, 0) at the output of encryption box 2, and to (–, –, B, Ω_T) at the output of encryption box 1, where A and B are some fixed differences in all the pairs (since they depend only on C_0, C_1, C_2 and Ω_T which are the same in all the pairs). As a result, encryption box 1 has difference Ω_T in the output of the fourth block, and its input is known to the attacker (as a plaintext block) XORed with the unknown fixed value B. Once we find the value of B, technique B can be used to find the key K_1.

The value of B can be found using a full-round characteristic of encryption box 1. If DES is used, it has probability about 2^{-63}, which (for many keys) will allow identifying the expected difference of the input to this box. Since the known plaintext block P_3 is XORed with the feedback from the previous block to form the input to the box, the differences satisfy $B = P_3' \oplus \Omega_P$, and B can be calculated for any right pair (P_3' is the difference between the plaintext block P_3 and its counterpart). The true value of B should be the most frequent resulting value, if the probability of the characteristic is not too low, and thus it can be identified (possibly using a huge memory of 2^{64} one-byte counters). This identification can be somewhat easier if we use the observation that we can find 52 bits of B even if we use only a 15-round characteristic, whose probability is about 2^{-55}, since we can predict the behavior of five S boxes in the 16th round (which have zero input differences).

This enhanced technique requires about 2^{66} chosen ciphertext tuples to find B, both feedbacks to P_3 (whose XOR is B) and the key K_1. It requires full-length characteristics, whose number of rounds is the same as the number of rounds of the attacked encryption box (sometimes characteristics with one round less can be used),

now find all the actual subkeys (actually only three actual subkeys are required). By analyzing the actual subkeys, we can find 55 independent parity bits of the DES key, 63 bits of the fixed value and one additional parity bit of both. By trying the two values of the unknown bit of the key we can find the complete key. The complexity of this attack is similar to the complexity of the independent key variant of the original attack on the ECB mode.

Whenever this enhancement uses a counting method to find the key (rather than the method used in the attack on the full 16-round DES), we must ensure that the fixed value is the same in all the tuples. For this, we have to choose the same C_1's and C_2's in all the pairs.

In the CBC|CBC|ECB mode, the other keys can be found by technique D (as in the attack on the triple CBC mode described later). In the CBC|ECB|CBC mode, K_3 can be found easily, since the input of box 3 can be easily calculated; then, K_1 can also be completed.

3.3 Technique C: A Technique using Linear Cryptanalysis

The basic technique can also be applied using linear cryptanalysis. In this technique, we do not choose pairs of messages and study their differences, as we do when differential cryptanalysis is used. Instead, we fix many blocks which are mixed with the inputs/outputs of the attacked encryption box, and we end up with the knowledge of the inputs and the outputs of the attacked encryption box XORed with some unknown fixed values. Since linear cryptanalysis is not affected by the combination of such fixed values, we can do the whole linear cryptanalysis, just as is done in the regular model (i.e. single ECB mode) — we just end up with parity bits combining key bits and bits of the fixed values. Since linear cryptanalysis can find the subkeys also when independent keys are used (i.e., when all the subkeys are independent), we can complete the encryption keys even in this more complex case, after we find several subkeys, rather than just one or two.

This technique can be applied to the modes attacked by techniques A and B. For example, to attack the CBC|ECB|CBC mode, it requires choosing many tuples of ciphertexts (C_0, C_1, C_2) where C_1 and C_2 should be fixed in all the tuples, and C_0 can be chosen at random. The resultant plaintext block P_2 is of the form $D_{K_2}(C_0 \oplus V_1) \oplus V_2$, where V_1 and V_2 are fixed values depending on the choice of the fixed ciphertext blocks C_1 and C_2. Linear cryptanalysis can find the key K_2 and the fixed values V_1 and V_2 (except one bit due to the complementation property: simultaneous complementation of K_2, V_1 and V_2 does not change the results). Then, attacks to find K_1 and K_3 can be mounted (even exhaustive search for each of them requires now only 2^{55}–2^{56} steps, and faster attacks *are* feasible).

This technique requires 2^{60} chosen tuples of ciphertext to find the key of the ECB component. The other keys of CBC|ECB|CBC can be found even by exhaustive

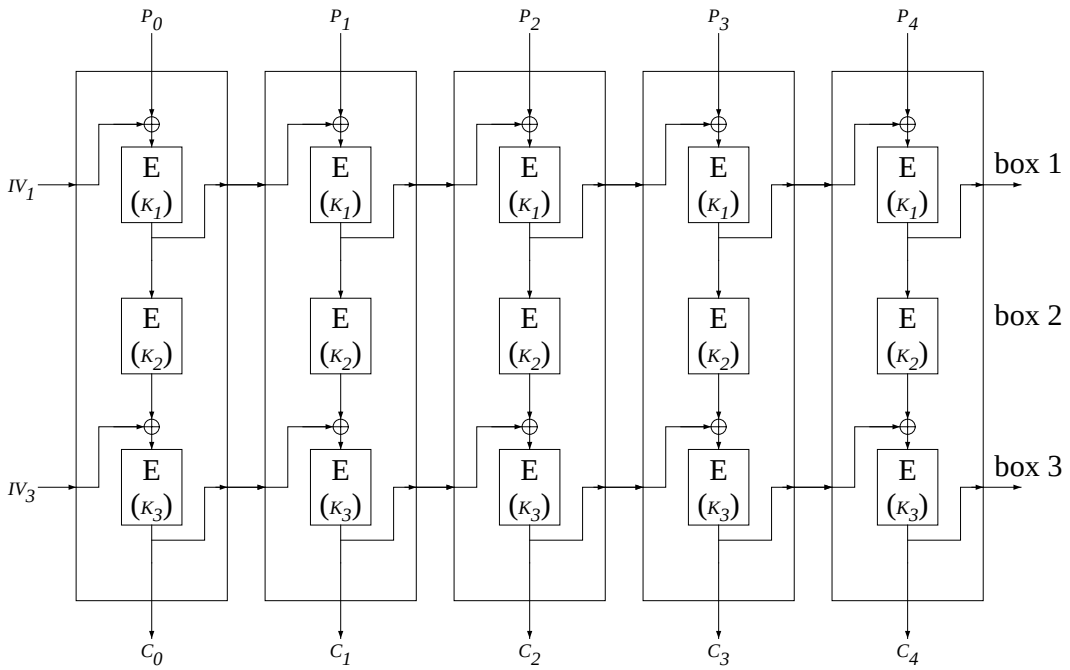

Figure 4. The triple mode: CBC|ECB|CBC.

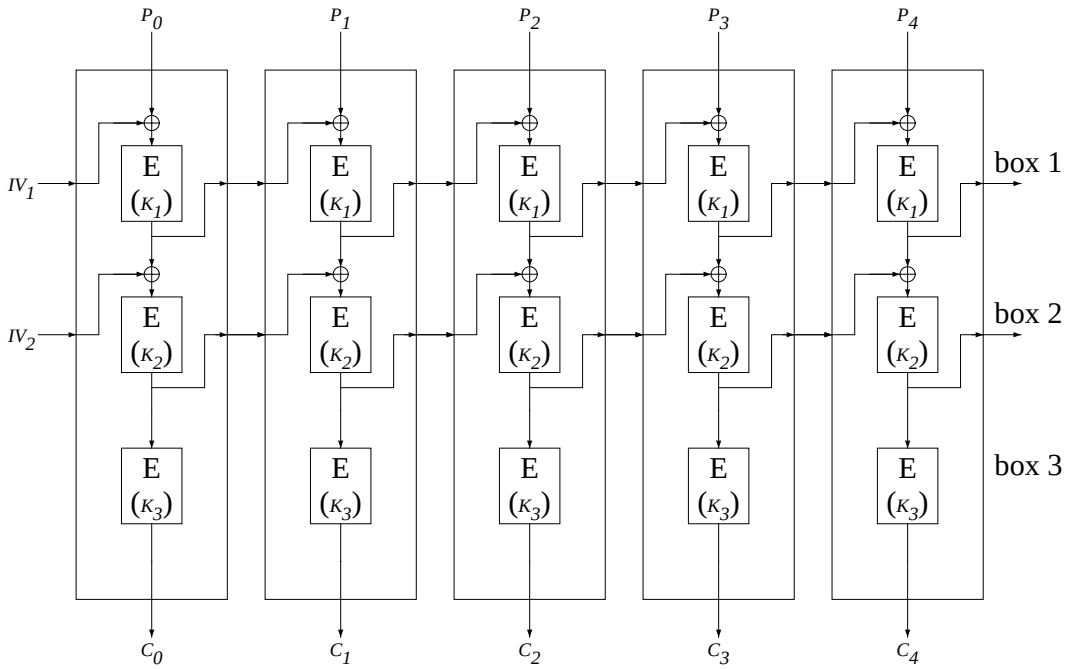

Figure 5. The triple mode: CBC|CBC|ECB.

Therefore, in the third blocks of the tuples, the differences of the output of box 1 are Ω_T, just as chosen by the attacker. Since the input of box 1 is the plaintext received by decryption of the triple mode, all the requirements for differential cryptanalysis of box 1 are satisfied. As a result, we can find the key used in box 1 by applying differential cryptanalytic attacks.

The attack described above assumes that the characteristic is set in the last rounds of box 1, and that the *R-attack is done on the first rounds. This attack can use quartets, octets or structures of any size by fixing C_1 and C_2 and playing with structures of C_0.

This technique, as described above, does not apply to the differential attack on the full 16-round DES[4,3], since the later requires the knowledge of actual plaintext (in our case: ciphertext) bits, and not only their differences. However, the 14 plaintext (ciphertext) bits required by the attack, are not known to the attacker just because they are XORed with a 14-bit constant. This constant can be found together with the key using a more extensive analysis.

Since the analysis phase of the attack on the full 16-round DES is faster by a factor of 2^{10} from the data collection phase, and since in our case the encryption times of the data collection phase costs $3 \cdot 3 = 9$ times more DES encryptions than the attack on the ECB mode, we conclude that the data analysis in our case takes about the same time as the data collection phase. Therefore, the complexity of a differential cryptanalytic attack on the first key of this triple mode is $3 \cdot 2^{47}$ chosen ciphertexts (2^{47} chosen ciphertext tuples). Using auxiliary structuring techniques, the number of chosen ciphertexts can be reduced to 2^{47}.

3.2 Technique B: Enhancement of the Basic Technique

An enhancement of the basic technique allows attacking modes whose plaintexts are mixed with feedbacks before they are fed into the first encryption box. Examples of such modes are CBC|ECB|CBC and CBC|CBC|ECB. These modes are described in Figures 4 and 5. This enhanced technique may also use any *R-attack, but requires finding more than one subkey. Thus, the number of required plaintexts is similar to the number of plaintexts required by the independent key variant of the differential cryptanalytic attack.

In these modes, we choose the differences of the tuples just as we do in the basic technique, but we receive less information from the received plaintexts. In the basic technique the inputs of encryption box 1 are known to the attacker. In the generalized modes attacked by this enhanced technique, the inputs of the encryption box in the ECB mode (boxes 2 and 3, respectively) are not known to the attacker. However, the value of this input XORed with an unknown fixed value (same in both members of the pair) is known. This fixed value may be mixed to the subkeys to form actual subkeys[3]. The independent-key variant of the differential cryptanalytic attack can

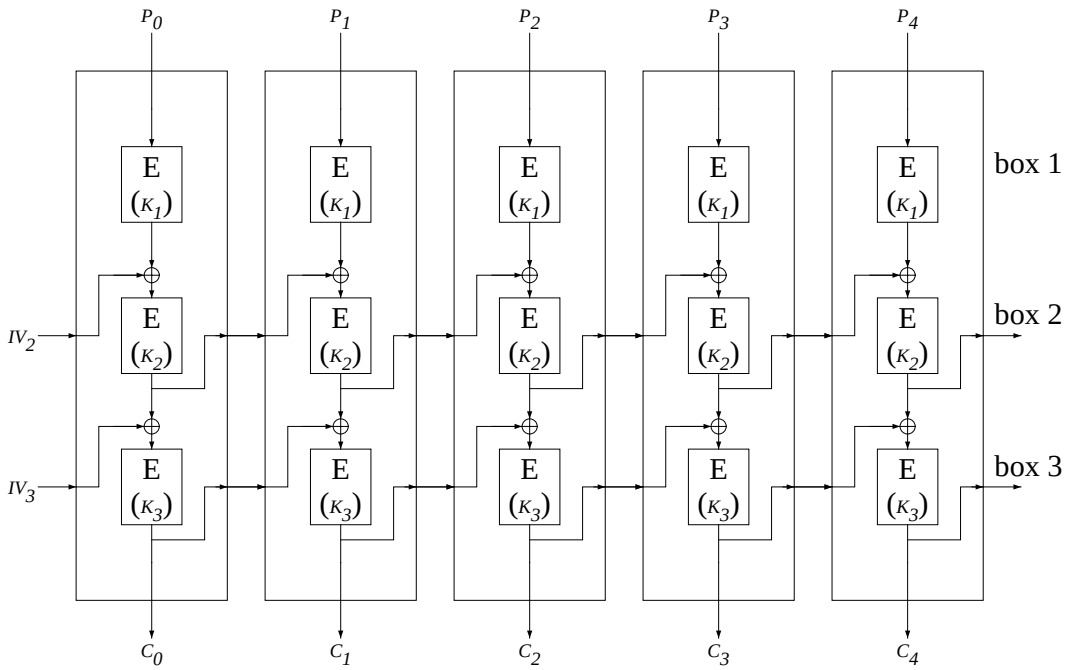

Figure 3. The triple mode: ECB|CBC|CBC.

One of the simplest forms of this technique attacks the ECB|CBC|CBC mode (see Figure 3) using a chosen ciphertext attack. Our aim is to feed the output of encryption box 1 (in the single ECB component) with pairs differing by the differences required for differential cryptanalysis. After these pairs are decrypted, the inputs of the encryption box are just the plaintexts we receive from the decryption of the triple mode. Thus, the regular differential cryptanalytic techniques (such as counting) can be applied. Note that due to the symmetry of DES (and most blockciphers), there is no technical difference between a chosen plaintext and a chosen ciphertext attack. Note also that if the same value of two successive ciphertext blocks is repeated twice in different positions in a ciphertext message (encrypted under the same keys with the ECB|CBC|CBC mode), the same feedbacks result in both positions, and any third block is decrypted into the same plaintext in both positions.

For the attack, the attacker chooses many pairs of tuples of blocks (C_0, C_1, C_2) and $(C_0 \oplus \Omega_T, C_1, C_2)$, where C_0, C_1, and C_2 are some arbitrary block values, and Ω_T is the difference required for differential cryptanalysis. If a differential attack with Ω_T requires n pairs to attack an ECB mode, the attacker should choose n tuples (C_0, C_1, C_2) and request to decrypt the $6n$ blocks consisting of all the pairs (C_0, C_1, C_2) and $(C_0 \oplus \Omega_T, C_1, C_2)$.

It is evident that the difference of the tuples is $(\Omega_T, 0, 0)$ for each pair. Due to the structure of the triple mode, the differences 0 cause differences 0 in the input of box 3, and after XORing these differences with the differences of the feedbacks, we result with differences $(-, \Omega_T, 0)$ in the output of box 2, where '$-$' denotes an unpredictable value. Similarly, the differences at the output of box 1 are $(-, -, \Omega_T)$.

3 Analysis

For the cryptanalysis of the modes of operation, we use several techniques. Most of these techniques select one of the encryption boxes in the modes of operation, inside one of the single modes, and feed it with the data required for differential or linear cryptanalysis. After the key of the encryption box is found, other (or the same) techniques are used to find the remaining keys (one at a time).

In the following sections we describe six cryptanalysis techniques, which introduce the most useful principles used to cryptanalyze multiple modes. Additional techniques can be developed using these principles. Each of the techniques finds one key. Unless otherwise indicated, the complexities quoted in the descriptions of these techniques are the complexities to find this one key. The total complexities of the attacks on the various modes are described in the summary. A few of the full attacks might become adaptive; however, in most cases the attacks remain non-adaptive.

We refer the encryption operations used in the modes of operation as *encryption boxes*, and number them with the index of the mode during the multiple encryption. The encryption boxes can actually apply decryption operations in particular single modes (in which during mode decryption, an encryption operation is to be used). In our discussion we use the terms input and output of the encryption boxes to be their input/output during mode encryption, regardless of whether we talk about mode encryption or mode decryption, and regardless of the particular operation in the encryption box (i.e., encryption or decryption). We keep the words plaintext and ciphertext to be the plaintext/ciphertext of the multiple mode, rather than to be the input/output of the encryption boxes. We also assume that the keys entering the encryption boxes are independent. We denote the key entering encryption box i by K_i, and the initial value of the ith single mode (if any) by IV_i (See Figure 2).

3.1 Technique A: The Basic Technique

Our basic technique for analyzing multiple modes of operation is to feed one of the underlying encryption boxes (in one of the single modes) with the data required for differential cryptanalysis. This may be done by choosing pairs of tuples of blocks in such a way that most blocks are the same in both pairs, and these blocks cause many internal values to be fixed when both tuples are encrypted/decrypted. One block should differ by the difference required for differential cryptanalysis, and it should cause this difference to appear in the input (or output) of one of the encryption boxes. In addition, we should be able to collect the output (or input) of this encryption block, up to XOR with some of the fixed internal values. This situation allows us to attack the encryption box by the regular differential attacks to which it is vulnerable (if it is vulnerable). This basic technique can be based on any differential cryptanalytic attack, and any successful *R-attack (either 0R, 1R, 2R or 3R-attack) can be applied.

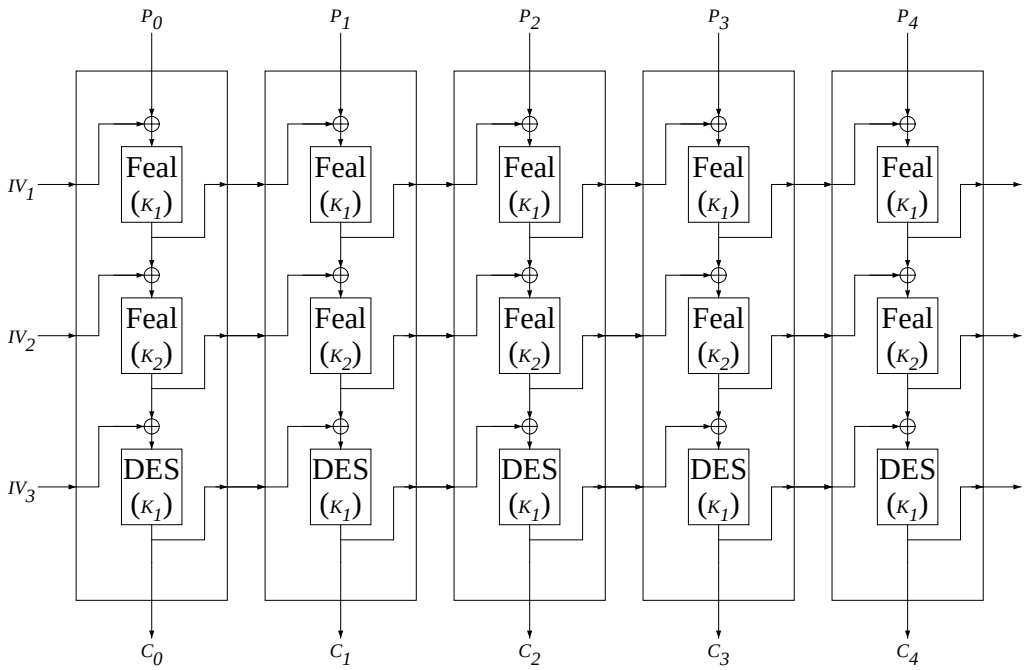

Figure 2. The triple CBC mode, using Feal, Feal and DES.

Conclusion 1 A multiple mode may not be weaker than its strongest component, if the component keys are chosen independently.

We show that this theorem holds *only* if the various components' keys are independent. In particular it does not hold for two-key triple modes (such as encrypt with K_1, encrypt (or decrypt) with K_2, and encrypt with K_1 again), since it might be that one key (K_1) is used both in the strongest component and the weakest component, and then we might find it by attacking the weakest component. For example, we study the case of a triple CBC mode which uses Feal[16,11] in its first two components, and DES[12] in the third, while the same key K_1 is used in both the first component and the third component (see Figure 2). By methods described in the next section, we can find the key K_1 of the first component using 2^{18} chosen ciphertexts. The key of the third component is the same as the key of the first component. The key of the second component can then be easily found using 1000 chosen ciphertexts (or 2^{24} known plaintexts). Therefore, the whole secret key of the multiple mode is found using about 2^{18} chosen ciphertexts within a few minutes. Note that the third component (which uses DES) by itself is much more resistant than the whole system, and cannot be attacked successfully by any known method with complexity smaller than 2^{43}.

be directly manipulated by the attacker. The chosen plaintext and ciphertext attacks are particularly applicable to double modes. They can cryptanalyze many modes that cannot be attacked by the simpler attacks and can attack other modes with a smaller complexity than other attacks.

We show that many multiple modes are weaker than the corresponding multiple ECB mode, when chosen plaintext, chosen ciphertext or chosen plaintext and ciphertext attacks are applicable. If a multiple mode combines several single modes, in which in each of them a different cryptosystem is used, and in which the keys of the various single modes are independent, the strength of the multiple mode might not exceed the strength of the strongest single mode component. If the various keys are not independent, the strength of the multiple mode might even be the same as of its weakest component. Two-key triple DES (triple ECB mode) is such an (already known) example [14].

We conjecture that operation modes should be designed around an underlying cryptosystem without any attempt to use intermediate data as feedback, or to mix the feedback into an intermediate round. Alternatively, if several encryptions are applied in each block, the best choice is to concatenate them to one long encryption, and build the mode of operation around the result.

This paper is divided to the following sections: In Section 2 we show that multiple modes are at least as strong as the strongest single mode contained within, when the keys of all the various single modes are independent. In Section 3 we analyse many multiple modes and describe our analysis techniques. In Section 4 we summarize the results.

2 The Strength of Multiple Modes

In this section we show that multiple modes of operation are not less secure than their strongest single mode component, whenever the keys of the various components are independent. This result holds in models in which the attacker has access to the plaintexts (and not only to their statistics). This result was already proved in the context of cascade ciphers in [7][1].

Let A and B be two modes and let C be the combined double mode C=AB, whose component keys K_A and K_B are chosen independently. The following theorem shows that C is not weaker than either of its components. It is similar to Theorem 5 in [7], whose proof holds in our case as well.

Theorem 1 The cracking problem of either A or B is efficiently reducible to the cracking problem of C=AB.

[1]It does not hold when the attacker has access only to the statistics of the plaintexts[10]. In our model the attacker always knows both the plaintexts and the ciphertexts.

Our attacks may be based upon any known attack on the underlying cryptosystems, and in particular upon differential cryptanalysis[3], linear cryptanalysis[9], improved Davies' attack[2], and exhaustive search. For reference we assume that the following complexities are required by these attacks: 2^{47} chosen plaintexts are required for differential cryptanalysis of DES, and 2^{61} if independent keys are used. 2^{43} known plaintexts are required for linear cryptanalysis of DES, and 2^{60} (?) if independent keys are used. Exhaustive search requires 2^{55}–2^{56} steps. For Feal-8[16,11] the complexities are 1000, 1000, 2^{24} (see [1]), 2^{24}, and 2^{64} respectively. Note that all the complexities of differential cryptanalysis hold for the ECB, CBC and the CFB modes (under chosen plaintext or chosen ciphertext attacks), and that the linear cryptanalysis complexities hold for the ECB, CBC, CFB and the OFB modes (under a known plaintext attack). (Note that an attack on the 8-bit CFB mode of DES with a reduced number of rounds was described in [15]). The best full-round differential characteristic of DES has probability about 2^{-63} and the best full-round differential characteristic of Feal has probability 2^{-16}. Unless otherwise indicated, we assume that DES is the underlying cryptosystem of the attacked modes. Throughout this paper, whenever we refer to the CFB and the OFB modes, we actually mean their full feedback variants, i.e., the 64-bit CFB and the 64-bit OFB, respectively.

Our attacks are of three major kinds: Chosen plaintext attacks are applicable to the ECB mode and potentially to other modes which were not designed to be immune to chosen plaintext attacks. We concentrate on chosen ciphertext attacks which are applicable to many of the modes which are immune to chosen plaintext attacks. For example, the CBC and the CFB modes are vulnerable to chosen ciphertext attacks (with attacks much simpler than the ones described in this paper).

The third kind of attacks (which we do not actually apply in this paper) generalizes the chosen plaintext and chosen ciphertext attacks into chosen plaintext and ciphertext attacks, in which the attacker can decide for each block whether he chooses the plaintext or the ciphertext. These attacks are not adaptive: the attacker can choose all the plaintext/ciphertext blocks before he receives the first encrypted/decrypted block. This model is very strong, since in practice no encryption chip or software allows changing direction from encryption to decryption and vice versa during the process of encryption/decryption. We can slightly reduce this demand by viewing an equivalent model which does not require changing encryption/decryption direction for each block. In this model, two chips loaded with the same key are required: one of them always encrypts and the other always decrypts. In this model, the attacks are adaptive chosen plaintext on one chip and an adaptive chosen ciphertext on the other chip, both executed in parallel. Whenever in the original attacks we have to encrypt a block, we feed the encrypting chip with the plaintext block, and feed the decrypting chip with the resultant ciphertext. Whenever in the original attacks we have to decrypt a block, we feed the decrypting chip with the ciphertext block, and feed the encrypting chip with the resultant plaintext. This model is more realistic in the sense that each chip either encrypts or decrypts, but the adaptive attack requirement causes this attack to work almost only when two such loaded chips may

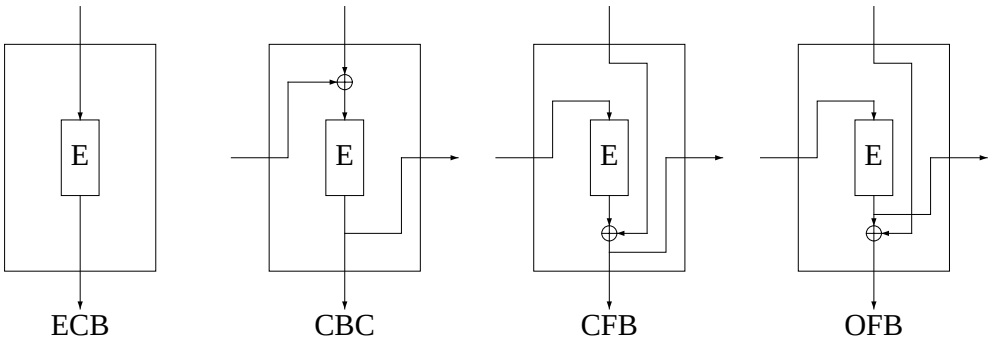

Figure 1. DES Modes of Operation.

attack does not let an attacker more information than a known plaintext attack. The CFB and OFB modes also allow encryption with a variety of blocksizes.

Although these modes were designed to protect against chosen plaintext attacks, there is no attempt to protect against known plaintext attacks. In the modes of operation of DES, if an attacker knows both the plaintext blocks and the ciphertext blocks, he can calculate the values of actual inputs and outputs of the underlying cryptosystem, and can mount any known plaintext attack.

Since the DES modes of operation were introduced (they are described in Figure 1), many new non-standard modes were suggested. The first of which is the counter mode in which a counter is incremented and used as a feedback, while there is no feedback from other plaintext blocks. Other examples of suggested modes are PCBC, which was also used as a MAC function in the Kerberos system, and PFF (Plaintext Feed Forward)[6], which is similar to decryption under CBC (except that it uses encryption rather than decryption internally). All these modes are designed around one encryption function, without inner-feedbacks. We will call such modes *single modes*.

In the recent years, several new attacks on DES were introduced[3,9,17,5,2]. These attacks have led many people in the cryptographic community to suggest stronger replacements to the DES, which can be either new cryptosystems or new modes of operation for the DES. The most popular new modes are the *multiple modes*, which are combined from several consecutive applications of single modes[6,8]. In particular, *triple modes* combined from three consecutive applications of single modes were suggested. These triple modes were claimed to be as secure as triple DES, although they do not have triple DES as a building block. An advantage of the triple modes and multiple modes when implemented in hardware is that their speed is just the same as of single modes, since the single modes can be pipelined.

In this paper we cryptanalyze many multiple modes of operation. In particular, we show that many triple modes are much weaker than triple DES, and that some triple modes are not much more secure than a single DES.

Cryptanalysis of Multiple Modes of Operation

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Abstract

In recent years, several new attacks on DES were introduced. These attacks have led researchers to suggest stronger replacements for DES, and in particular new modes of operation for DES. The most popular new modes are triple DES variants, which are claimed to be as secure as triple DES. To speed up hardware implementations of these modes, and to increase the avalanche, many suggestions apply several standard modes sequentially. In this paper we study these *multiple* (cascade) modes of operation. This study shows that many multiple modes are much weaker than multiple DES, and their strength is comparable to a single DES.

We conjecture that operation modes should be designed around an underlying cryptosystem without any attempt to use intermediate data as feedback, or to mix the feedback into an intermediate round. Thus, in particular, triple DES used in CBC mode is more secure than three single DES's used in triple CBC mode. Alternatively, if several encryptions are applied to each block, the best choice is to concatenate them to one long encryption, and build the mode of operation around it.

1 Introduction

The Data Encryption Standard[12] has several modes of operation[13] in which it can be used. These modes were devised to have a limited error propagation, to allow synchronization in data communications, to hide patterns in the plaintexts and to protect against chosen plaintext attacks on the underlying cryptosystem and against dictionary attacks. In the Cipher Block Chaining (CBC) mode and the Cipher Feedback (CFB) mode, each ciphertext block depends on all the previous plaintext blocks, by using the previous ciphertext block during encryption. The Output Feedback (OFB) mode was designed to allow precomputation of a major part of the encryption process, and to act as a pseudo-random bit generator. In this mode, a chosen plaintext