SoK: Security Evaluation of SBox-Based Block Ciphers

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Abstract. Cryptanalysis of block ciphers is an active and important research area with an extensive volume of literature. For this work, we focus on SBox-based ciphers, as they are widely used and cover a large class of block ciphers. While there have been prior works that have consolidated attacks on block ciphers, they usually focus on describing and listing the attacks. Moreover, the methods for evaluating a cipher's security are often ad hoc, differing from cipher to cipher, as attacks and evaluation techniques are developed along the way. As such, we aim to organise the attack literature, as well as the work on security evaluation.

In this work, we present a systematization of cryptanalysis of SBox-based block ciphers focusing on three main areas: (1) Evaluation of block ciphers against standard cryptanalytic attacks; (2) Organisation and relationships between various attacks; (3) Comparison of the evaluation and attacks on existing ciphers.

Keywords: Security Evaluation · Block Ciphers · Substitution Box · Cryptanalysis

1 Introduction

In an increasingly data-driven world, the security and privacy of our data and communications is of vital importance. Block ciphers are widely used cryptographic primitives, which are building blocks that form the cornerstone of security schemes which protect this data. The block cipher as a cryptographic primitive has been popularized by the publication of the Data Encryption Standard (DES) by the United States National Bureau of Standards in 1977. Since then, there has been extensive study on block cipher design and the weaknesses they present. Block ciphers are commonly used today in algorithms such as the Advanced Encryption Standard (AES), which is prevalent in critical real-life applications everywhere.

The security evaluation of block ciphers is an active and important research area, with a copious amount of literature amassed on the topic to this day. Cryptanalysis describes this specific field of security evaluation in the context of studying the effectiveness of attacks against cipher designs. Modern cipher design has placed great importance on the resilience of their designs against known attacks. As such, much of the literature in this area has been concentrated on proving/arguing the security of ciphers against these attacks or demonstrating how these attacks may be applied to existing schemes (or part thereof).

This paper will present a systematization of cryptanalysis of SBox-based block ciphers focusing on three main areas: (1) Evaluation of block ciphers against standard cryptanalytic attacks; (2) Organisation and relationships between various attacks; and (3) Comparison of the evaluation and attacks on existing ciphers. More generally, we aim to compile, organize, and process the vast trove of knowledge on attacks of block ciphers, and present a high-level treatment of these attacks as applied to the security evaluation process of different ciphers. In particular, we will focus on SBox-based ciphers, as they are widely used and cover a large class of block ciphers.

ORGANIZATION. This paper proceeds as follows: Section 2 provides the readers with some background on block ciphers and attacks, and lays some groundwork necessary for the rest of the paper. Next, Section 3 consolidates the existing literature on SBox-based block cipher attacks and distills the essence of a varied list of cryptanalysis techniques, through the lens of the concrete security evaluation on an existing cipher. Then, Section 4 condenses the main properties of each attack to draw connections and perform classifications between different attacks. Finally, Section 5 provides a case study of the security evaluation processes adopted by designers of various popular SBox-based block ciphers, while Section 6 draws a conclusion to the paper.

OUR CONTRIBUTIONS. During the block cipher design process, there is a multitude of considerations to take into account when evaluating attacks. Due to the vast expense of literature available on block cipher cryptanalysis, it is easy to overlook certain aspects of attacks during security evaluation. This paper aims to amalgamate the information in this domain in a concise and easily-accessible manner, so that the reader may easily extract the information that they require to make informed choices when performing security evaluation.

The objectives of this work are as follows: first, to inform the reader on the current state of cryptanalysis techniques on SBox-based block ciphers, as they pertain to a security evaluation framework, enabling focus on techniques that will be useful in evaluating a specific cipher with its particular structure and characteristics and a given adversarial model; and second, to highlight the importance of a comprehensive security evaluation process. We hope to achieve these objectives with the following contributions:

- We revisit and formalize key notions associated to SBox-based block cipher. In particular, we revisit the definitions of Generalized Feistel Networks (GFN) and Substitution Permutation Networks (SPN), as well as the relationship between distinguisher-finding and key-recovery attacks. We formalize these precisely in the context of SBox-based block ciphers.

- We review fourteen cryptanalytic techniques from the literature that we determined to have been the most impactful toward modern cipher design. We take care to capture these distinct techniques using a novel and consistent syntax, thereby unifying these tools for use by future cipher designers. Specifically, we identify how each cryptanalytic technique can be used to build distinguishers, how these distinguishers can be extended to key recovery attacks, and what techniques exist to protect ciphers against such attacks.

- To help contextualize cryptanalytic techniques for those new to the area, we draw connections between known cryptanalytic techniques, including the fourteen major ones presented above. We also revisit the classification of these attacks with refreshed definitions of structural, statistical and algebraic definitions.

- Finally, we provide a novel case study of popular schemes that emerged from cryptographic competitions. In particular, we compare the security assurances given by the schemes' designers (with respect to our highlighted cryptanalysis techniques) to attacks that have emerged in the 20+ years that have passed. From this, we gain novel insight into how security evaluations evolve over time, and draw conclusions that could be of interest to future research, cipher designers and cryptographic competitions.

2 Background

In this section, we provide background on SBox-based block ciphers, including GFN and SPN (with variants). We also give an overview on cryptanalytic techniques and attack models.

Block ciphers, SBoxes. A block cipher is a method of encryption where plaintexts are encrypted in n-bit blocks to n-bit ciphertext blocks. Given key k, a block cipher specifies an encryption algorithm E_k and a decryption algorithm D_k, such that $D_k \circ E_k$ is the identity on n-bit plaintexts [VTJ14].

An SBox (Substitution-box) is an b_1-bit to b_2-bit function that typically has a non-linear algebraic expression and is used to inject non-linearity into a cipher system. There has been a great deal of research performed on constructing good SBoxes, and the impact of SBoxes on cryptanalysis is fairly well studied. As such, many ciphers are constructed with SBoxes as their underlying backbone. In our discourse, we only consider ciphers that derive their non-linearity from SBoxes.

GFNs. Feistel networks form the basis of a widely used design philosophy to design block ciphers by the modern cryptographic community. The classical vanilla Feistel structure (as deployed in DES) works as follows: Given an n-bit string, the Feistel structure divides it into two halves L (left) and R (right) called branches. During each round, a (non-linear) round function $F(R, k)$ is applied to the right branch and the result is XORed with the left half in the operation $\phi : (L, R) \leftarrow (R, L \oplus F(R, k))$, where k is the round subkey produced by the key scheduling algorithm. The branch positions are then swapped before the next round. More generally, the n-bit string may be divided into smaller strings instead of halves, and a branch permutation is applied to swap their branches around [VTJ14].

A key feature of the Feistel structure is the similarity between the encryption and decryption processes. In particular, the classical Feistel structure as constructed above provides invertible transformations independently of whether the round function F is invertible or not. Additionally, Feistel structures also allow for efficient spreading of the diffusion (changing one bit affects many bits) and confusion (each bit depends on many bits) properties of the round function between branches. In particular, we can construct a Pseudo-Random Permutation (PRP) from just 3 rounds of a classical 2-branch balanced Feistel network [LR88]. This allows a designer to fully concentrate on the security properties of the round function when making security evaluations [Nyb96]. Note that while the round function can be constructed in a myriad of ways, we are only interested in SBox-based constructions here.

We can further generalize the classical notion of a Feistel structure, by considering similar structures which spread the diffusion and confusion properties of the round functions across branches in different ways. For instance, certain ciphers such as MISTY1 apply the round function to the actual branches via the round operation $\phi : (L, R) \leftarrow (R, F(L, k) \oplus R)$ [Mat97].

In order to encapsulate all these variations, we look at a broader class of ciphers known as Generalized Feistel Networks (GFN). These include: unbalanced Feistel networks with expanding or contracting round functions; alternating Feistel networks, where the rounds alternate between contracting and expanding steps; nested Feistel networks where the round functions are themselves Feistel networks; type-1, type-2, and type-3 Feistel networks, each of which uses 1, 2, or 3 n-bit to n-bit round functions respectively to create a kn-bit block cipher for some $k \geq 2$; and numeric variants of any of the above, where one enciphers numbers in $\mathbb{Z}_N$, for some $N \in \mathbb{N}$, instead of enciphering binary strings. Some examples of block ciphers that use generalized Feistel networks include Skipjack (an unbalanced Feistel network), BEAR/LION (alternating), MISTY1 (nested), CAST-256 (type-1), CLEFIA (type-2), and MARS (type-3) [HR10].

SPNs. Another popular design philosophy for block ciphers is the Substitution-Permutation Networks (SPN) structure. While exceptions (such as KATAN/KTANTAN [DDK09]) exist, a vast majority of block ciphers that are not GFN are either SPN or a variant of it. SPN derive their security by composing several rounds of interleaving substitutions and

Table 1: Classification of various notable SBox based ciphers by structure.

GFN Ciphers			**Non-GFN Ciphers**		
CLEFIA	KASUMI	DES	**AES**	SASAS	ARIA
SKIPJACK	**Camellia**	LBlock	**Serpent**	SKINNY	SAFER
LOKI	**MISTY1**	GDES	3-WAY	KHAZAD	KLEIN
GOST	TripleDES	Biham-DES	LED	LowMC	CRYPTON
CAST	DES-X	NewDES	PRINTCIPHER	SQUARE	**Hierocrypt**
Blowfish	TWINE	Piccolo	HADES	PRESENT	NOEKEON
FEAL	**Twofish**	WARP	**SC2000**	GIFT	
	MARS				

permutations. Although weak on its own, a line of substitutions followed by a permutation has good "mixing" properties: substitutions (often via SBoxes) add to local confusion and permutations diffuse the local confusion to the more distant sub-blocks, triggering an avalanche effect over multiple rounds. Some variants of SPN use linear or affine mappings instead of bit permutations to achieve better diffusion in fewer iterations. Such networks are called Substitution-Linear Networks (SLN) or Substitution-Affine Networks (SAN) respectively. Rijndael/AES is a prominent example of an SLN cipher. In this work, for brevity, we will refer to all SPN/SLN/SAN schemes collectively as "SPNs".

To concretize these definitions, we collected a list of notable SBox-based ciphers in the literature. While we do not claim that this list is exhaustive, we believe it contains all schemes with substantial visibility (i.e. citations). We note that every scheme on our list was either a GFN or SPN, as detailed in Table 1.

In Section 2 we will give an overview of distinguishers and attacks on these SBox-based ciphers (from either one or both of these classes). In Section 5, we do a detailed literature review of nine of these schemes, which are **bolded** in Table 1.

ATTACKER MODELS. In this paper, we will be providing an exposition of the various attacks applied on block ciphers. Before we proceed, we would like to first make a brief comment on distinguisher-finding attacks and key recovery attacks. In most cases, the tools developed by the various cryptanalytic techniques do not allow attackers to recover the key directly, but instead allow them to find a $m-$round distinguisher. These distinguishers are often based on a certain property or characteristic constructed from the attack, and enable attackers to distinguish a correct instantiation of the attacked cipher with the correct key, from a random function or permutation with a higher than random probability.

Distinguishers may be extended to key-recovery attacks through an appropriate application of the distinguisher and a good choice of PT-CT pairs to propagate our desired characteristic so that the conditions of the distinguisher can be met. In particular, for the Differential Cryptanalysis (DC), Linear Cryptanalysis (LC), Zero-Correlation Linear Cryptanalysis (ZCLC), Impossible Differential Cryptanalysis (IDC) and Integral attacks, the extension from a distinguisher attack to a key-recovery attack typically works as follows: Suppose our distinguisher attack indicates that a set of input-output pairs exhibits a certain characteristic that can be distinghished from random permutation through a certain number of rounds, which we shall label as the core rounds. Then, we can add additional rounds before and after the core rounds, and select appropriate PT-CT pairs that will propagate through the additional rounds to a set of input-output pairs to the core rounds that exhibit our desired characteristic if the subkey guess to these additional rounds is correct. We can then identify, and hence recover, the correct subkey by observing the subkey guess for which the distinguishing property holds. This set of input-output pairs to the core rounds differs from attack to attack.

3 Overview of Cryptanalytic Techniques

In this section we will provide a short discourse on several attack techniques, mainly on how they may be applied as distinguisher attacks. This is because our focus is on security evaluation, where one aims to ensure that no distinguishers of sufficiently high probability exist for r rounds. To this end, we will highlight the techniques used to find longest possible distinguishers and estimate their probabilities. These include the main algorithms used, as well as mixed-integer linear programming (MILP), SAT and constraint programming approaches, which have recently gained popularity. We have included in Table 3 a brief description of the distinguishers and security evaluation techniques.

In all the subsections that follow, we will use X and Y (and subscripted versions of these) to denote intermediate cipher states. In general, X will refer to a state closer (in terms of rounds) to the plaintext, while Y is closer to the ciphertext. The states X and Y are usually a few rounds away from the the plaintext and ciphertext respectively, since key recovery attack extends the distinguisher.

DIFFERENTIAL CRYPTANALYSIS Differential cryptanalysis, first published in [BS91], is a chosen plaintext attack that exploits predictable difference propagations, i.e. $\Delta X \rightarrow \Delta Y$ for r rounds with higher than random probability. Here, ΔX refers to a known fixed difference pattern for the cipher state X. For later sections, we may specify the difference pattern as $\Delta \rightarrow \Delta^*$ or $\nabla \rightarrow \nabla^*$ to illustrate the attacks.

Observe that the difference propagation is deterministic for linear portions of the cipher but probabilistic for the SBox portions. An approach to evaluate cipher's security against differential cryptanalysis approximates the probability of a differential path by taking the product of the differential characteristic probability of the active SBoxes [Dae95]. Hence evaluating the security reduces to finding a differential path with the minimal number of active SBoxes. The AES designers used this method, showing that since the minimum number of active SBoxes in any 4-round differential trail is 25 and the SBox differential probability is 2^{-6}, the maximum differential probability of $2^{-6\times 25} = 2^{-150}$ for any 4-round differential trail [DR03].

The first generic algorithm for differential path searching is Matsui's branch-and-bound search algorithm [Mat95]. This breadth-first search was later improved using search patterns [OMA95], using a pre-search [AKM97] and with various other techniques in [BZL15, JZD21]. MILP has also been used to construct automatic differential (and linear) path searches including work in [WW11, MWGP12].

In Sony's original specification documentation on CLEFIA, a computer search yielded a lower bound of 28 active SBoxes for any 12-round differential trail [Son07]. Together with the maximal SBox differential probability of $2^{-4.67}$, they showed that the maximal differential probability for 12 rounds is $2^{-4.67\times 28} = 2^{-130.76}$. Wu–Wang's paper [WW11] had a more pessimistic result, with a lower bound of 24 active SBoxes for any 13-round differential trail in CLEFIA.

In truncated differential cryptanalysis, distinguishers are $\Delta X \rightarrow \Delta Y$, where the explicit word or byte differences are not specified, and only stated as zero or nonzero difference. This relaxation of the differential attack was first introduced in [Knu95] and used in meet-in-the-middle attacks against CLEFIA and Camellia [LJWD15]. The concept of truncated differentials has been applied to differential-linear cryptanalysis as well as in the construction of impossible differential distinguishers.

LINEAR CRYPTANALYSIS The linear cryptanalysis attack, first studied in [MY93], is a known plaintext attack that uses linear approximations, i.e. equations of the form $\alpha \cdot X = \beta \cdot Y$ (for some vectors (α, β) called masks) which hold with biased probability greater than $\frac{1}{2}$. One can linearly approximate the SBoxes to get the bias for a linear path.

To concatenate the probabilities of multiple such linear approximations, Matsui introduces the piling-up lemma [Mat94], which assumes that the approximations are independent.

Table 2: Attacks and Corresponding Security Evaluation Methods

Attack type	Distinguisher structure	Method of Security Evaluation
Differential (DC)	$\Delta X \rightarrow \Delta Y$ with high probability	Use duality between DC and LC. Matsui's path search [Mat95] and improvements [OMA95, AKM97, BZL15, JZD21]. MILP tools [MWGP12, WW11]
Linear (LC)	$\alpha \cdot X = \beta \cdot Y$ with high probability	
Impossible Differential (IDC)	$\Delta X \rightarrow \Delta Y$ with zero probability	Use duality between IDC and ZCLC. Miss-in-the-middle methods ($\mathcal{U}$, UID), Wu–Wang [WW12], MILP [CJF+16, ST16] and CP [SGL+17] tools
Zero Correlation Linear (ZCLC)	$\alpha \cdot X = \beta \cdot Y$ with probability 1/2	
Differential-Linear (DLC)	Cipher has two components $E = E_1 \circ E_0$ E_0 with $\Delta X_0 \rightarrow \Delta X_1$ E_1 with $\alpha \cdot X_1 = \beta \cdot X_2$ with high probabilities	Combine longest differential and linear paths, estimate differential-linear bias based on independence assumptions [BDK02a, LGZL10, Lu12] or estimate bias from closed form [BLN15]
Boomerang	Cipher has two components $E = E_1 \circ E_0$ E_0 with $\Delta X_0 \rightarrow \Delta X_1$ ${E_1}^{-1}$ with $\Delta Y_0 \rightarrow \Delta Y_1$ with high probabilities	Combine long differential paths with high probability. Use Boomerang Connectivity Table [CHP+18, BHL+20], or Boomerang Difference Table [WP19] to find trails and probability or a method by Song et al. [SQH19] MILP, SMT/SAT and CP tools [DDV20, HBS20]
Higher Order Differential	$\Delta^d X \rightarrow \Delta^d Y$ with high probability	Heuristic approach, give upper bound on degree of the polynomial describing the cipher after r rounds [BCD10]
Related Key Differential	$(\Delta X, \Delta K) \rightarrow \Delta Y$ with high probability	Use DC method on key schedule (upper bound) [Son07] or estimate probability [CZK+11]
Related Key Boomerang	Cipher has two components $E = E_1 \circ E_0$ E_0 with $(\Delta X_0, \Delta K) \rightarrow \Delta X_1$ ${E_1}^{-1}$ with $(\Delta Y_0, \Delta K) \rightarrow \Delta Y_1$ with high probabilities	Combine differential paths on key schedule [Son07] or estimate probability [CZK+11]
Integral	Known pattern in the X leading to known patterns in Y (patterns: active, zero or balanced)	Tracing the division property [Tod15b] and bit-based variant [TM16] MILP [XZBL16], SAT [EKKT19], CP [SGL+17] tools
Slide	Cipher E is composed of functions $F(X, K)$, X, X' such that $F(X, K) = X'$	Heuristic evaluation of key schedule uniformity e.g. independent round constants provide security [Son07]
Interpolation or other algebraic attacks	Various algebraic relations between X and Y	Heuristic approach, estimate the number of equations and terms [CP02, Son07], or algorithm for linear sum security [Aok00]
Meet in the Middle (MiTM)	Cipher has three components $E = E_2 \circ E_1 \circ E_0$ Distinguisher on E_1 only affected by subkeys in E_0, E_2	Ad-hoc approaches using the distinguishers above, or search tools [LWWZ14, DF16, SSD+18]

It was also observed that for a given linear relation, there could be multiple possible intermediate linear paths, combining to give a higher linear probability. Nyberg introduced the term linear hull to refer to the set of all such linear trails [Nyb95]. Despite these, the independence assumption appears reasonable for many ciphers, and when one linear trail has a high bias, it tends to dominate the linear hull [Hey02].

Hence, security evaluations tend to involve finding a linear trail with a minimal number of active SBoxes and computing the linear probability by the piling-up lemma. For example, for CLEFIA, there are at least 30 active SBoxes for any 12-round linear path and the maximum linear probability of the SBoxes is $2^{-4.38}$, yielding a maximal linear cryptanalysis probability of $2^{-4.38 \times 30} = 2^{-131.40}$ for 12 rounds [Son07].

Biham observed that linear and differential cryptanalysis are structurally similar [Bih95]. For example, they have similar security estimation methods. Matsui followed up on this correspondence, observing that a path $a \to b$ is a differential trail of a cipher if and only if it is a linear hull of the dual structure, where the dual cipher is constructed by observing that an XOR operation after an F function and a three-forked branch before the F function are mutually dual [Mat95].

To account for differential and linear cryptanalytic techniques in cipher design, two approaches were considered. The wide trail strategy [DR01], which was used in AES design, aims to design the round transformations such that there are no trails with few active SBoxes. Another method, decorrelation [Vau03], constructs ciphers from primitives with sufficient pseudorandomness, using this to compute that the maximal differential and linear probabilities and prove that are too low to mount a linear or differential attack. However, COCONUT, constructed via decorrelation was shown to be vulnerable to some attacks where differential (and linear) distinguishers were used in combination [Wag99, BDK02a].

IMPOSSIBLE DIFFERENTIAL CRYPTANALYSIS Impossible differential attacks were first used by Knudsen [Knu98] and generalised and named in [BBS99]. These attacks use impossible difference propagations, i.e. $\Delta X \to \Delta Y$ with zero probability as a distinguisher. The general attack strategy is as follows. Firstly select many structures of chosen plaintexts and sieve the pairs satisfying the required output differences. Secondly, for each sieved pair, discard the wrong subkeys which cause the partial encryption and decryption to match the impossible differential. Lastly, analyse enough pairs and sieve the correct subkey.

Some work to construct impossible distinguishers include the miss-in-the-middle $\mathcal{U}$ method [KHS+03] and its generalisation, the UID method [LWLG09]. In these approaches, the cipher functions are modelled as a matrix applied on vectors to study the difference propagation. They consider four cases: zero difference, nonzero fixed difference, nonzero unspecified difference and unknown difference. In particular, they are built from truncated differentials.

However, the miss-in-the-middle structure does not account for impossible differentials with information feedback. These are structure where there is no contradiction in the middle matching point, instead, the matching point forces some constraints on other parts of the cipher, which lead to a contradiction. Many known impossible differential distinguishers are of this form such as those on 9-rounds CLEFIA [TTS+08b]. To account for these, Wu–Wang use a more generic approach [WW12], which was proven to find all impossible differentials of a cipher that are independent of the SBox choices [SLR+15]. MILP tools [CJF+16, ST16] and constraint programming [SGL+17] have also been used to find impossible differential distinguishers.

ZERO CORRELATION LINEAR CRYPTANALYSIS Zero correlation linear cryptanalysis, based on linear approximations with probability $\frac{1}{2}$, i.e. unbiased or with zero correlation, is an extension of linear cryptanalysis first proposed by [BR11] and later extended to include multiple zero correlation distinguishers [BW12].

The correlation between two functions f, g is $C(f, g) = 2(Pr(f(x) = g(x)) - 1$, i.e. it measures the likelihood of two functions matching each other. In the cryptanalytic setting, we consider $C(\alpha \cdot X, \beta \cdot Y)$, where (α, β) is the mask. For any non-trivial linear approximation (α, β) of an n-bit permutation, the correlation value can be evaluated with 2^{n-1} input-output pairs (x, y) [BR11]. This is used to evaluate a key guess, as in the attack launched in [BGW⁺14].

In the linear cryptanalysis case, the correlation is as high as possible, since the masking is chosen so that $Pr(\alpha \cdot X = \beta \cdot Y)$ is high. With this in mind, zero correlation linear cryptanalysis can be viewed as the linear counterpart of impossible differential cryptanalysis. Bogdanov–Rijmen suggested a relationship between the impossible differential and zero correlation linear distinguishers. It was later shown that a zero correlation linear hull of a block cipher is an impossible differential characteristic of the corresponding dual cipher and vice versa [SLR⁺15]. This allows an attacker to run the same distinguisher-finding tools as for impossible differential distinguishers.

Square, Saturation, Integral Cryptanalysis Square attacks are based on the dedicated attack constructed on SQUARE [DKR97], which was later extended to other ciphers processing data blocks in fixed-size words at a time [NBP⁺01]. This included the first notion of the balanced property, when the words in a particular position over the set of plaintexts sum to zero. Square attacks were used against Hierocrypt [BRN⁺02] as well as AES-192 and AES-256 [GM00]. A variant of the square attack, the saturation attack, was introduced in [Luc02]. An improvement to the original square attacks includes the partial sum technique [FKL⁺01].

Square and saturation attacks are precursors of integral cryptanalysis [KW02]. In an integral attack, an attacker tries to predict the properties of the sum of all ciphertext values, i.e. whether words in a certain position are all the same (constant) or all different (active) or the words sum to a known specific value, e.g. zero (balanced). To construct integral distinguishers, these properties were further generalised to the division property which can be traced based on the cipher operations [Tod15b]. A variant of the division property, specifically an extension to the bit-based case, was constructed in [TM16]. Using the division property, one can use MILP [XZBL16], SAT solvers [EKKT19] or constraint programming [SGL⁺17] to automate the construction of integral distinguishers.

Integral distinguishers can be derived from impossible differentials and zero-correlation linear differentials. In particular, both r-round ZCLDs and IDs yield r-round integral distinguishers [SLR⁺15]. This was used on CLEFIA [YC16]. Moreover, for CLEFIA, an 8-round distinguisher was first proposed by the designers [Son07] and used to construct an 11-round saturation attack [WW08]. Subsequently, 9-round distinguishers were found in [LWZ12, YC16] and used in attacks of up to 15 rounds.

Differential-Linear Cryptanalysis The differential-linear attack was introduced by Langford–Hellman as a method to combine differential and linear attacks [LH94]. A notable differential-linear attack was on full round COCONUT98, in spite of its provable security claim on both differential and linear security [BDK02a]. Suppose that the cipher (or sub-cipher) E can be decomposed as $E = E_1 \circ E_0$, where there is a differential (or truncated) characteristic on E_0 given by $\Delta X_0 \to \Delta X_1$ (with a specified difference pattern $\Delta \to \Delta^*$) and a linear approximation of E_1 given by $\alpha \cdot X_1 = \beta \cdot X_2$, both of high probabilities.

Consider an pair of plaintexts $(X_0, X_0 \oplus \Delta)$. Applying E_0 maps the plaintexts to the same round state as X_1, while applying E maps them to the same round state as X_2. Hence we can apply the linear correlation and obtain $\alpha \cdot E_0(X_0) = \beta \cdot E(X_0)$ and $\alpha \cdot E_0(X_0 \oplus \Delta) = \beta \cdot E(X_0 \oplus \Delta)$ with high probabilities. Then taking the XOR of these equations and using the differential characteristic, with high probability we get

$$\alpha \cdot \Delta^* = \alpha \cdot (E_0(X_0) \oplus E_0(X_0 \oplus \Delta)) = \beta \cdot (E(X_0) \oplus E(X_0 \oplus \Delta))$$

The bias that this linear approximation holds, called the differential-linear bias, has been studied heuristically by Biham et al. [BDK02a], Liu et al. [LGZL10] and Lu [Lu12] under different independence assumptions. It is not clear whether these assumptions hold in general - Biham et al. assume that the distribution of $\beta \cdot (E(X_0))$ and $\beta \cdot E(X_0 \oplus \Delta)$ is independent and uniformly distributed, but Lu shows that this might not be the case [Lu12]. Further work by Blondeau et al. used a relation between linear and differential cryptanalysis to give a closed form for the bias, only under the assumption that two sub-ciphers are independent [BLN15]. However, evaluating this form is computationally intensive.

RECTANGLE AND BOOMERANG ATTACKS The boomerang attack was discovered by Wagner as an extension of differential cryptanalysis [Wag99]. It involves decomposing the cipher E into two components, i.e. $E = E_1 \circ E_0$ and using two unrelated differential characteristics (or truncated differentials), $\Delta \to \Delta^*$ for E_0 and $\nabla \to \nabla^*$ for E_1^{-1}, with high probabilities (rather than one long differential with a low probability). A boomerang distinguisher is a quartet of plaintext-ciphertext pairs, such that P, P', Q, Q' and corresponding ciphertexts C, C', D, D' satisfy the following:

- The pairs (P, P') and (Q, Q') each satisfy $\Delta \to \Delta^*$ after applying E_0
- The pairs (C, D) and (C', D') each satisfy $\nabla \to \nabla^*$ after applying E_1^{-1}

Wagner used this technique to construct longer distinguishers, breaking the cipher COCONUT, which was constructed to be provably secure against differential attacks [Vau03]. A disadvantage is that the boomerang attack requires rather strong conditions - both adaptively chosen plaintext and adaptively chosen ciphertext queries are needed to run the attack.

Following this, there have been several extensions to the boomerang attack. The amplified boomerang attack removes the chosen-ciphertext condition at a cost of more chosen-plaintext queries [KKS01], while the rectangle attack builds on the amplified attack, using multiple boomerang distinguishers, where the differences in the center of the cipher are not fixed, as long as they sum to zero [BDK01]. Dunkelman et al. introduced the sandwich attack, where a short middle layer is added so the cipher is decomposed as $E_1 \circ E_m \circ E_0$ [DKS14]. A variant of boomerang attack, which also requires adaptively chosen plaintexts and ciphertexts is the yoyo attack. It was first introduced in [BBD+99] and later extended to SPN structures and AES in [RBH17].

In Wagner's original attack, the two differentials are assumed to be independent. However, their dependencies have shown to either aid the attack (boomerang switches [Vau03] , [BK09]) or reduce its effectiveness [Mur11]. Some tools constructed to account for these dependencies include the boomerang connectivity table [CHP+18, BHL+20], the boomerang difference table [WP19], a method by Song et al. to determine the choice of middle length [SQH19], as well as some SMT/SAT, MILP and CP solvers [DDV20, HBS20]. More recently, Kidmose–Tiessen have conducted a theoretical analysis of the probabilities of these distinguishers [KT22].

RELATED KEY DIFFERENTIAL CRYPTANALYSIS Related key attacks were first studied by Biham [Bih94] and later extended using differential cryptanalysis by Kelsey et al. [KSW96]. Related key differential cryptanalysis is an extension of differential cryptanalysis where the key difference is known or chosen by the attacker, and is part of the differential characteristic. To launch the attack, one attempts to find a triplet of differences in the plaintext, ciphertext and key i.e. $(\Delta X, \Delta K) \to \Delta Y$ that holds with high probability.

Related key differential cryptanalysis has been used to construct a full attack on AES-256 by exploiting the key schedule's slow diffusion and local collisions from matching differential properties between the key schedule and the cipher rounds [BKN09]. The attack has a 2^{131} time, 2^{65} memory complexity and requires 2^{35} related keys on average.

In [CZK+11], Choy et al. present a framework to evaluate a block cipher's security against related key differential and boomerang attacks. They showed that security against these attacks follows if the number of active SBoxes in a differential characteristic of the key schedule and the number of active SBoxes in the differential characteristic of the main cipher, conditioned on subkey differences from the key schedule, is large enough. Specifically, by Bayes' theorem they have the following:

$$Pr(\Delta P, \Delta K \to \Delta C) = Pr(\Delta K \to \Delta K_0, \ldots \Delta K_m) \cdot Pr(\Delta P \to \Delta C | \Delta K \to \Delta K_0, \ldots \Delta K_m)$$

where the first term considers the key schedule differential characteristic and K_i are the subkeys, K is the key, and P, C are the plaintext and ciphertext respectively. The authors denote the first probability in the product as p_k and the second as $p_{c|k}$. In practice, it is often sufficient to consider the p_k component. For example, for CLEFIA, the designers evaluated its security against the related key differential attack by consider the differential characteristic of the key schedule [Son07]. Since it has the same round structure as the main cipher, the same differential probability computed for DC was used to show CLEFIA's security in the related-key setting.

RELATED KEY BOOMERANG AND RECTANGLE ATTACKS The first mention of related key rectangle attacks was by Kim et al. in [KKH+04], where the authors combine a differential with a related key differential. Biham et al. and Hong et al. concurrently revised this notion to combine two related key differentials in the attacks[BDK05b, HKLP05]. This method of cryptanalysis was also used by Biryukov–Khovratovich to attack full AES-192 and AES-256 [BK09].

In related key boomerang or rectangle attacks, the cipher E is decomposed into two components, $E = E_1 \circ E_0$ and a related-key differential is applied on each sub-cipher. Leveraging on the boomerang attack style, the related key variant is able to use shorter related-key differentials for the similar length distinguisher, so there is potentially less diffusion of differences in the subkeys. However, the attack also inherits the issues faced in estimating complexity for the boomerang attack. Kim et al. conducted experimental verification and more rigorous analysis of the related key boomerang and rectangle attacks, observing that while the results are on average close to theoretical, there is high variance in the exact probability, i.e. works well for some keys but fails for others [KHP+12].

For the first related key differential, we let p_k refer to the key schedule differential characteristic probability and $p_{c|k}$ refer to the conditional probability. We define q_k and $q_{c|k}$ in the same way for the second related key differential. Then Choy et al. show in [CZK+11] that:

- the cipher is secure against a related key boomerang attack if the probability $(p_k q_k)^2 (p_{c|k} q_{c|k})^2$ is less than the inverse of the keyspace
- that there will be insufficient plaintexts to launch the attack if $(p_{c|k} q_{c|k})^2$ is less than the inverse of the plaintext space

In practice, one may take an upper bound: in [Son07], the designers evaluated security by showing that $(p_k q_k)^2$ is less than the inverse of the keyspace.

SLIDE ATTACKS Slide attacks were first used in an unpublished manuscript in 1998, which was later made available in [Saa19], to recover the secret SBoxes in GOST. Officially introduced by Biryukov—Wagner [BW99], it is the first attack that is often independent of the number of rounds. The attack works if the cipher can be decomposed into a product of identical permutation functions $F(x, k)$, where k is the fixed secret key. The F function may consist of more than one cipher round, but the key k should be "easy" to extract given two plaintext-ciphertext pairs $F(x_1, k)$ and $F(x_2, k)$.

To run the attack, the attacker first finds plaintexts P, P' such that $F(P, k) = P'$, then the corresponding ciphertexts C, C' also satisfy $F(C, k) = C'$. The set (P, C), (P', C') is called a slid pair and can be used by the property above to extract the key k. Slide attacks require some periodicity or self-similarity in the round keys.

Improvements to the slide attacks include two variants: sliding with a twist and complementation slide [BW00], which extend the attack on new classes of ciphers (Feistel ciphers with two round self-similarity, and four round self-similarity if these variants are combined). A variant in [BDK07] finds slid pairs more efficiently. Another attack that depends on self-similarity on the rounds is the reflection attack [Kar07, DDKS15]. Slide attacks have also been used in combination with algebraic attacks [CBW08].

Since CLEFIA uses round constants independent of each round, the designers argue that it does not have a self-similarity property that can be exploited to construct a slide attack [Son07].

HIGHER ORDER DIFFERENTIAL CRYPTANALYSIS Higher order differential cryptanalysis generalises differential cryptanalysis, exploiting higher order differentials over several rounds that hold with high probability. We will denote a d-th order differential as $\Delta^d X \to \Delta^d Y$. This attack was first introduced by Lai in [Lai94] and further developed by Knudsen in [Knu95].

In particular, observe that if the algebraic degree of the ciphertext (or the round state a few rounds before) as a function of the plaintext is d, the d-th order differential over is a constant and can be used as a distinguisher in a higher order differential attack. Ciphers such as a reduced version of MISTY1 were shown to be vulnerable against higher order differential distinguishers, despite being secure against differential attacks [CV02].

It is difficult to analytically ensure security against higher order differential attacks, i.e. ensure that no high probability higher order differentials exist. Heuristically, a high algebraic degree for several rounds for the cipher makes it unlikely that a higher order differential attack will work. For a d-th order differential, 2^{d+1} plaintexts are needed to compute the derivative, so the complexity of the attack is higher with a higher order.

A trivial bound for the algebraic degree of r rounds is $(\deg F)^r$, where F is the round function, however, the degree of the composition of F might grow much slower. The first improvement of this bound was provided by Canteaut–Videau [CV02] and later by Boura et al. [BCD10]. More specifically, given a cipher round function F (on state size n bits) and any function G also on n bits, Boura et al. showed that

$$\deg(G \circ F) \leq n - (n - \deg G)/(b-1)$$

where b is the bitsize of the SBoxes. This gives a heuristic upper bound on the degree of F^r.

INTERPOLATION AND CUBE ATTACKS The main idea behind interpolation attacks is that the ciphertext can be expressed as a polynomial in terms of the plaintext. Given enough plaintext/ciphertext pairs, one can use the Lagrange interpolation formula to recover the coefficients of this polynomial. After constructing the polynomial of the ciphertext decrypted by one round, one more plaintext ciphertext pair is used to verify the guess. For the correct last-round key, the plaintext and ciphertext decrypted one round would also satisfy the polynomial constructed.

In the first work on interpolation attack by Jakobsen—Knudsen in [JK97], this attack was applied to a variant of SHARK which was provably secure against differential and linear cryptanalysis. Interpolation attack was shown to work well against ciphers with low algebraic degree. Improvements on the interpolation attacks include using the Moebius transform to reduce the time complexity [DLMW15], removing the requirement to brute force the last-round key and interpolation of only one coefficient in the polynomial to reduce the memory requirement [LP19]. The low/constant memory attack is restricted to some key-alternating and Feistel network structures. Modifications to the original attack include [KID01], where Kurosawa et al. observed that Jakobsen—Knudsen underestimated the number of plaintext/ciphertext pairs needed, i.e. the key found might not be unique.

They used Rabin's root finding method to find the set of equivalent keys in this case and derived an upper bound for the number of equivalent keys in the chosen plaintext case.

To analyse the attack effectiveness, Youssef—Gong considered how the degree of the interpolated polynomial varied depending on the choice of the irreducible finite field polynomial used as well as if the linear transformation were applied on input or output bits of the SBoxes (or the round function) [YG01]. Aoki generalised this attack to the linear sum attack and developed an algorithm to evaluate the security of byte-oriented ciphers under this attack [Aok00]. Aoki also showed that security against the linear sum attack implies security against higher order differential attacks.

Cube attacks, first introduced in [DS08b], involve setting up and solving a linear system of polynomials in $GF(2)$ describing the cipher. It has a computationally intensive offline phase and an online phase. In the offline phase, given access to an encryption oracle and choice of both the plaintexts and keys, the attacker generates a superpoly in terms of the key bits. This is evaluated on multiple chosen plaintexts in the online phase to get a linear system of polynomials. The name of the attack follows from the "cube" $y[I]$ in the superpoly, where $y[I]$ refers to a partial assignment of variables to a cartesian product $A_1 \times \cdots \times A_n$.

Several variants of cube attacks have been proposed, and were categorised in [COOP22]. While cube attacks mainly work on stream ciphers, a method of finding cube distinguishers for dynamic cube attacks on block ciphers was presented in [ARSA15] and the division property was used to find cube distinguishers in [EGB20].

OTHER ALGEBRAIC ATTACKS Other algebraic attacks include extended linearisation (XL), extended sparse linearisation (XSL) attack and Gröbner basis attack, including Buchberger's algorithm [Buc06], F4 [Fau99] and F5 [Fau02], and ElimLin [CB07].

These algorithms simplify and solve a system of equations with some constraints. Yang et al. give asymptotic security estimates under these attacks, by estimating the solving efficiency and observe that the attacks generally work better in conjunction with subkey guessing [YCC04]. In general, the complexity and efficiency of these algorithms are not agreed upon in the cryptographic community.

In the XSL attack introduced in [CP02], an attacker forms a system of multivariate quadratic (MQ) equations describing the cipher. Although MQ systems are generically hard to solve, in the AES and SERPENT cases, the systems are overdefined and sparse and thus solvable in slightly lower than brute force time complexity [CP02]. The attack uses a small number of plaintext-ciphertext pairs. Compared to other attacks like DC/LC, security against this attack does not grow exponentially with the number of rounds.

To counter this attack, Tran et al. studied SBox modifications to increase the algebraic complexity and reduce the sparsity of the MQ system [TBD08]. Meanwhile, Murphy—Robshaw considered a variant of the XSL attack on AES with all operations written in $GF(2^8)$ to simplify the system Mathematically [MR02]. However, the high degree of complexity in the attack makes it hard to estimate. The effectiveness of XSL attacks have been highly disputed [RM07, CL05].

Gröbner basis attacks have been applied to AES-256, with slightly better than brute force complexity [ZCX17]. Practically while there has been explicit construction of block ciphers that are resistant to DC/LC attacks but are weak against Gröbner basis attacks [BPW05], no cipher other than Keeloq has been proved vulnerable to algebraic attacks [CBW08].

MEET-IN-THE-MIDDLE AND VARIANTS The meet-in-the-middle attack was first introduced by Diffie–Hellman on Double DES [DH77]. The attack works by splitting the cipher into two components $E = E_1 \circ E_0$ as before. Given plaintext-ciphertext pairs, we may perform partial encryption (and respectively partial decryption), aiming to get a matching intermediate state.

If the round keys in E_1, E_0 are independent (as in the Double DES case), and assuming the case where E is split evenly, then partial encryption (and partial decryption) each only need to be done on half of the keyspace. This reduces the complexity from $2^{|K|}$ to $2^{|K|/2+1}$, however there is a memory tradeoff, as intermediate states have to be stored. For this attack to work, both E_1 and E_0 have to operate only using part of the key.

The meet-in-the-middle attack was extended by Demirci et al. to attack IDEA [DST03] and Demirci–Selçuk to attack AES [DS08a]. In these two papers, Meet-in-the-Middle is used as a generic framework to construct attacks from distinguishers. In their model, a cipher E is decomposed into three $E = E_2 \circ E_1 \circ E_0$, where there is a known distinguisher on the E_1, and only a portion of the key bits in E_0, E_2 are involved in the computation to test whether the distinguisher is satisfied. This approach, later known as Demirci-Selçuk meet-in-the-middle attack, has been applied to CLEFIA and camellia [LJWD15], as well as to generic balanced Feistel structures [GJNS14]. Improvements on the attack include Dunkelman et al.'s differential enumeration technique for memory data tradeoffs [DKS10].

To perform searches for Demirci-Selçuk meet-in-the-middle attacks, some automated tools have been developed including Derbez–Fouque's exhaustive search tool in C/C++ [DF16], Lin et al.'s integer optimization approach [LWWZ14] and Shi et al.'s constraint programming approach [SSD+18].

Another extension of Meet-in-the-Middle attacks are biclique attacks, which were first introduced against hash functions in [KRS12] and later extended to AES in [BKR11a], as well to PRESENT, Piccolo and LED [ÇKB12]. The main idea of biclique attacks is to partition the keyspace, so that one can use meet-in-the-middle attack. For each subset of keys S, one constructs a biclique, which is a complete bipartite graph where the edges match cipher round states values X to Y if there is a key from S such that X is encrypted to Y. The biclique is denoted as a set $\{\{X\}, \{Y\}, \{S\}\}$ of values from the key and two round states, and can be constructed from related key differentials [BKR11a]. In [AFL+14] Abed et al. developed a software framework to construct bicliques and determine the resulting attack complexity.

Other meet-in-the-middle attacks include collision attacks (including attacks in [WFC04]) and the slicing attack [Küh02], which we will not discuss in detail.

OTHER ATTACKS For attacks in this section, we only include the references to the first mentions, but leave further descriptions and methods of security evaluations of these attacks to future work.

Some attacks extend the cryptanalytic methods the sections above, exploring relations among a larger set of plaintext-ciphertext pairs. Examples of these include polytopic cryptanalysis [Tie16], which extends differential cryptanalysis (or impossible differential cryptanalysis), and partitioning cryptanalysis [HM97], which extends linear cryptanalysis. Other attacks combine several methods from the sections above, these include differential-bilinear attacks, higher-order linear attacks and combining boomerang with other attacks[BDK05a].

The related key approach has also been extended to make use of other distinguishers. The attacks under this framework include related key square, impossible differential, differential-linear and slide attacks. Generally, security evaluation again these other related key attacks are not specific to the attack model. Instead they are heuristic arguments that lack of uniformity in the key schedule suggests the ciphers' security against generic related key attacks, as in the security evaluation of SERPENT [ABK98].

Some other block cipher attacks we did not discuss above include the nonlinear invariant attack [TLS19], the invariant subspace attack [LAAZ11] (and a generalisation known as subspace trail attacks [GRR16]) and mixture differential cryptanalysis [Gra18] (also known as the exchange-invariant attack [BR19a]). We also did not cover attacks which investigate the general statistical features of ciphers, such as the bit distributions. These include the generic statistical attack, which was used on various ciphers including the following [GC90, GHJV00, Pes06].

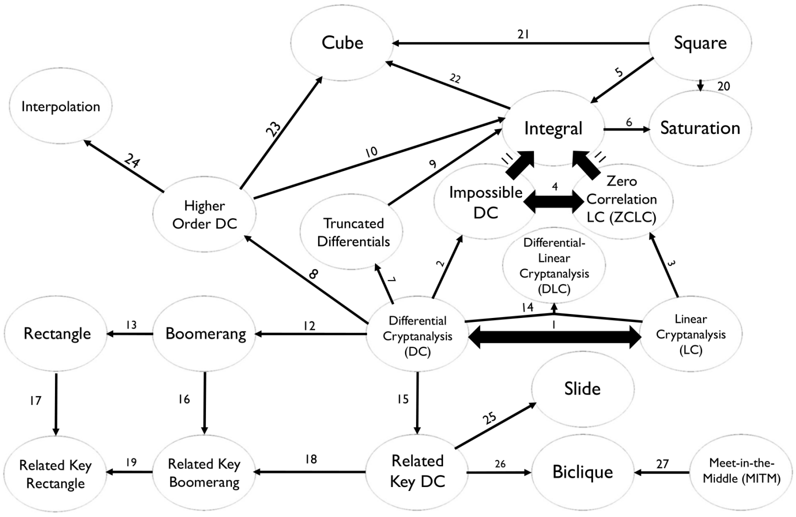

Figure 1: Map of how various attacks are related to each other. The edges indicate that the corresponding attacks are related. A more detailed explanation of these relations can be found in Section 4.1 and Table 3

4 Classifications and Connections

During the design process of a block cipher, it is paramount to consider the degree of effectiveness of various possible cryptanalytic techniques on the cipher. Due to the sheer volume of literature available on different attacks and their variants applied to different types of ciphers, the process of performing analysis of a new cipher design based on existing literature may be a highly daunting and involved task.

This section aims to ameliorate some of the pain during navigating the cipher design process by performing classifications on, and by drawing connections between, the different attacks presented in Section 3.

4.1 Association Map of Attacks

Here, we attempt to draw connections between different attacks through the use of an association map in Figure 1. This map presents these connections in a compact way for ease of reference, so that readers are able to observe the specific links between their attacks of interest at a glance. We note that the attacks and relations presented in this map are non-exhaustive. For instance, we omitted attacks such as the Slide Attack and Gröbner Basis Attacks as they do not connect well with the rest of the map. Additionally, we did not include the direct relation between Truncated Differentials and the Saturation Attack (i.e. that their distinguishers are identical up to a time-memory tradeoff [BN15]) as they are both connected through the Integral Attack, which we allude to in the map. For a more detailed exposition of these attacks and connections, we refer the reader to Section 3. Each node here corresponds to an attack and the edges between the nodes in the map indicates an association between the attacks in the nodes.

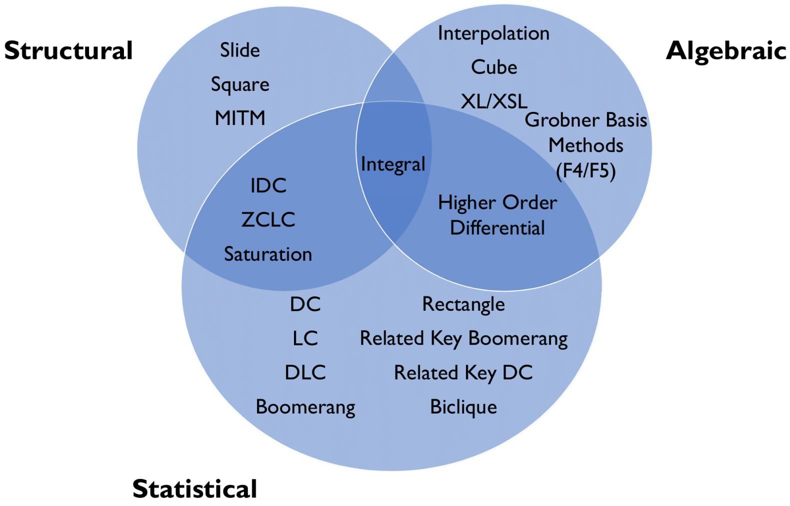

Figure 2: Rough classification of attacks based on approaches taken.

We hope that this map serves as a good starting reference for the study of block cipher cryptanalysis techniques. We shall provide a brief comment on the relations between the different attacks in Table 3 below. For the sake of brevity, we are unable to provide a complete discussion of the technical details of each relation in this paper. Instead, we refer the reader to the corresponding list of references in Table 3 to learn about the respective associations between the attacks in greater detail. Here, we opine that the DC, LC, Impossible DC, ZCLC and Integral attacks are the core attacks to consider during the block cipher evaluation process, in terms of their historical impact on existing ciphers and how influential or connected they are in relation to other attacks. For general purposes, we advise the reader to begin reading up on DC, and work through the map by traversing the edges in ascending order of their labels, and consulting their corresponding references in the table, as well as the references of any new attacks encountered in the process.

The thick arrows between the LC and DC nodes, as well as the IDC, ZCLC and Integral nodes, indicate extremely close and important associations between these attacks.

The connections between LC and DC are well known, and covered in Section 3 of this paper. In particular, the bi-directional edge between the LC and DC nodes refer to the one-to-one correspondence between the differential trails of a cipher structure $\mathcal{E}$ and linear hulls of its dual structure $\mathcal{E}^{\perp}$ [Mat95].

A ZC linear hull always indicates the presence of an integral distinguisher, while an $r-$round ID of a cipher structure $\mathcal{E}$ necessarily implies the existence of an $r-$round integral distinguisher of its dual structure $\mathcal{E}^{\perp}$. Additionally, there exists a one-to-one correspondence between IDs in a cipher structure $\mathcal{E}$ and ZC linear hulls in its dual structure $\mathcal{E}^{\perp}$ [SLR^{+}15]. Furthermore, it has been shown that once we have an ID distinguisher on r rounds involving M differentials, we obtain a ZC distinguisher on the same r rounds involving M linear approximations, and vice versa [BBW14].

Table 3: Descriptions of relations between attacks, and their corresponding references.

Edge Label	Description	Reference(s)
1	Mutually applicable on dual cipher structures, i.e. if there exists an $n-$round linear hull on cipher $\mathcal{E}$, then there exists an $n-$round differential trail on its dual structure $\mathcal{E}^{\perp}$.	[Bih95], [Mat95]
2	Probability Zero Characteristic.	[BBS99]
3	Correlation Zero Characteristic.	[BR11]
4	Mutually applicable on dual cipher structures, i.e. if there exists an $n-$round zero-correlation linear distinguisher on cipher $\mathcal{E}$, then there exists an $n-$round impossible differential trail on its dual structure $\mathcal{E}^{\perp}$.	[BLNW12]
5	Extension of Attack beyond AES-like ciphers.	[KW02]
6	Generalization to saturated subspaces which induce non-random output distributions.	[CS09]
7	Considering Multiple Sub-Differentials.	[Knu95]
8	Generalization to Higher Orders, i.e. taking derivatives $\Delta_{a_1,\ldots,a_i} f(x) = \Delta_{a_1,\ldots,a_{i-1}} f(x - a_i) - \Delta_{a_1,\ldots,a_{i-1}} f(x)$ for $i \geq 1$.	[Knu95]
9	Truncated Differential where the probability of having zero difference in q bits corresponds to the uniform probability $p = 2^q$, where q is the size of the output mask.	[KW02], [BN15]
10	Specific instance when considering $s-$order differentials over $\mathbb{F}_{2^k}$, where s is the size of the input mask. Related by the Division Property.	[KW02], [Tod15b]
11	Zero Correlation Linear Hull indicates the existence of an Integral Distinguisher. More specifically, an r-round Zero Correlation Linear Hull can be used to construct an r-round Integral Distinguisher. An Impossible Differential Distinguisher of cipher $\mathcal{E}$ always implies the existence of an Integral Distinguisher of its dual structure $\mathcal{E}^{\perp}$.	[BBW14], [SLR$^+$15]
12	Applied twice to two sub-ciphers.	[Wag99]
13	Targets differential characteristics over the entire space of intermediate differentials, rather than just the highest differential.	[BDK01]
14	DC applied to upper half of cipher, LC applied to lower half of cipher.	[LH94]
15	Applied to Key Schedule.	[Bih94], [KSW96]
16	Applied to Key Schedule.	[BDK05b]
17	Applied to Key Schedule.	[BDK05b]
18	Applied twice to two sub-ciphers.	[BDK05b]
19	Targets differential characteristics over the entire space of intermediate differentials, rather than just the highest differential.	[BDK05b]
20	Generalization to saturated subspaces which induce non-random output distributions.	[CS09]
21	Algebraic variant that also extracts secret variables from the characteristic.	[TIHM17]
22	Algebraic variant that also extracts secret variables from the characteristic.	[TIHM17]
23	Conceptually similar over $\mathbb{F}_2$.	[DS08b]
24	Generalization to recovering the coefficients of polynomials in s variables over $\mathbb{F}_{2^{m/s}}$, where m is the size of the PT/CT.	[JK01]
25	Variant of Related Key Attack, specifically when a cipher has self-related keys	[BDK08]
26	Often used in its construction.	[BKR11b]
27	Application with the aid of complete bipartite matchings, or bicliques, between intermediate states and key guesses.	[BKR11b]

4.2 Classification of Attacks

In Fig. 2, we classify the attacks into three categories: structural, statistical, and algebraic. The attacks belonging to each of these categories vary in their attack philosophy, in terms of their approach taken to derive distinguishers. This follows from generic literature on cryptanalytic techniques [Rim09, Jun05].

Structural attacks only require knowledge of the round structure of the cipher, without

Table 4: Adversarial models required for attacks. † DC may be a known PT attack under certain specific scenarios. ‡ Albeit rare, there exist known PT + chosen key difference RK differential attacks [Bih94]. ∗ There exists one instance of a CT-Only Slide Attack on DESX [BW00], and Slide Attacks may be improved under stronger adversarial models (Chosen PT/CT/ Adaptive Chosen PT etc.), provided the Weak Key Class exists.

Attack type	Attack Model
Differential	Chosen PT†
Linear	Known PT
Impossible Differential	Chosen PT
Zero Correlation LC	Known PT
Differential-Linear	Chosen PT
Boomerang	Adaptive Chosen PT/CT
Higher Order Differential	Chosen PT
RK Differential	Chosen PT‡ + Chosen Key Difference
RK Boomerang	Adaptive Chosen PT/CT + Chosen Key Difference
Integral	Chosen PT
Slide	Known PT∗ + Weak Key Class
Interpolation	Chosen PT + Possible Weak Key Class
MITM	Known PT/CT + Weak Key Schedule

details such as the specific functions or the SBox used. One of the earlier mentions of this branch of attack is in Structural Cryptanalysis of SASAS, where Biryukov and Shamir construct an attack which is independent of the specific SBox and affine functions in the encryption [BS01]. A textbook example of a structural attack is the integral attack.

Statistical attacks attempt to construct statistical patterns using plaintext ciphertext pairs, in order to distinguish the cipher from random permutations, using this to recover the key. These attacks exploit the probabilistic properties of block ciphers, and may require knowledge of the differential characteristics of SBoxes present in the ciphers.

Algebraic attacks exploit algebraic relations involving both the inputs and the outputs of some cipher component. The attacks often involve collecting, then solving a system of simultaneous equations in a large number of unknowns, possibly using algebraic tools.

Besides the above classification of attacks based on attack philosophy, we also observe that the security assumptions adopted by each attack is different. More specifically, some attacks have more stringent requirements than others that may render them impractical to a weaker adversarial model. These models may be classified into five broad categories, in descending order of strength: CT-Only, Known PT, Chosen PT, Chosen CT, and Adaptive Chosen PT/CT (i.e. it is easiest/ requires the least resources for an attacker to perform a CT-Only attack). In the following table, we shall summarize the (strongest) adversarial model enabled for a list of highlighted attacks.

5 Case Studies: Competition Schemes

In this case study, we are interested in how security evaluation has been done in popular SBox-based block ciphers *by the cryptography community.* This means we take into consideration not only the assurances and cryptanalysis performed by the scheme's designers, but also the subsequent work done in the literature to validate or invalidate these claims. Since many of the popular schemes used in real-world applications were proposed some time ago, there is a vast amount of associated security evaluation literature. As such, our case study serves two purposes: (1) as a survey of the cryptanalytic security evaluation of popular SBox-based block ciphers and (2) as a breadth-wise study comparing the claims made by scheme designers to subsequent results from the open literature. In short, we get a glimpse into how security evaluations of popular schemes mature over time.

In this section, we first overview how we delimited the case study. In Section 5.1, we provide a summary table (see Table 5) which covers the security claims made on nine popular schemes within the literature, and draw some conclusions from this. We also provide a detailed survey on the available literature for each of these schemes which were distilled to make Table 5 and cover some of the unique nuances that come with evaluating each scheme. However, in order to ensure comprehensiveness in these surveys we must defer it to Appendix 5.2 for brevity.

Scheme selection. Since we wanted our case study to encompass popular schemes that are used in real-world applications and have undergone substantial security analysis by academia, we looked to block cipher competitions which the international cryptography community participated actively in. Our schemes come from three sources:

- **Advanced Encryption Standard:** This NIST competition selected the block cipher AES (Rijndael) in 2001 [AES14]. We consider the five "finalists" of this competition in our case study.
- **CRYPTREC:** This was a process initiated by the Japanese government in 2000 to evaluate and recommend a broad set of cryptographic techniques for government and industry use [CRY22]. We consider all block ciphers from the "e-Government" and "Candidate" lists published in 2013.
- **NESSIE:** This was a European research project to identify secure cryptographic primitives that ran from 2000-2003. We consider all recommended block ciphers from this competition.

With the above shortlist, we omitted RC6 (from the AES process) and SHACAL-2 (from NESSIE) since they are not SBox-based block ciphers. We also omitted CIPHERUNICORN and 3-Key Triple DES (from CRYPTREC), since the former has not been studied extensively[1] and the latter will soon be deprecated for all applications by NIST [BR+18]. This left us with nine schemes: AES (Rijndael), Camellia, CLEFIA, Hierocrypt, MARS, MISTY1, SC2000, Serpent and Twofish.

Survey Methodology. One can divide the claims made in cryptanalytic security evaluation literature into two groups which we call the "'defender POV" and "attacker POV". The intuitive difference is the stance taken by the authors – whether they are trying to prove that a scheme is secure or insecure. The "defender POV" includes any research done to provide assurances as to a scheme's resilience against particular forms of cryptanalysis. This includes more formal approaches, such as those discussed in Section 3, but also more heuristical arguments about why certain attacks would be "difficult to carry out", such as those that are used in design documents or subsequent security evaluations that are a part of the competition process. The "attacker POV" includes any work that attacks the scheme or a part thereof. This usually takes the form of cryptanalysis of round-reduced variants of the scheme, possibly with some scheme elements (e.g. whitening rounds) omitted.

In this case study, we included all works, to the best of our knowledge, which study the security of our schemes (or part thereof) in a standard attacker model in relation to one or more cryptanalytic techniques. In particular, we allow works that focus on reduced variants of the cipher (e.g. reduced round variants with no whitening rounds) but disallow further modifications to the scheme (e.g. variants with a secret SBox). In terms of the attacker model, we encompass all standard attacker models (e.g. chosen/known plaintexts, all-keys/weak-key attacks) but omit works which give the attacker additional inputs (e.g. side channel attacks). Also, for ease of comparison, this section will assume the adversary's goal is key-recovery (as opposed to distinguishing attacks) since that is the more potent model.

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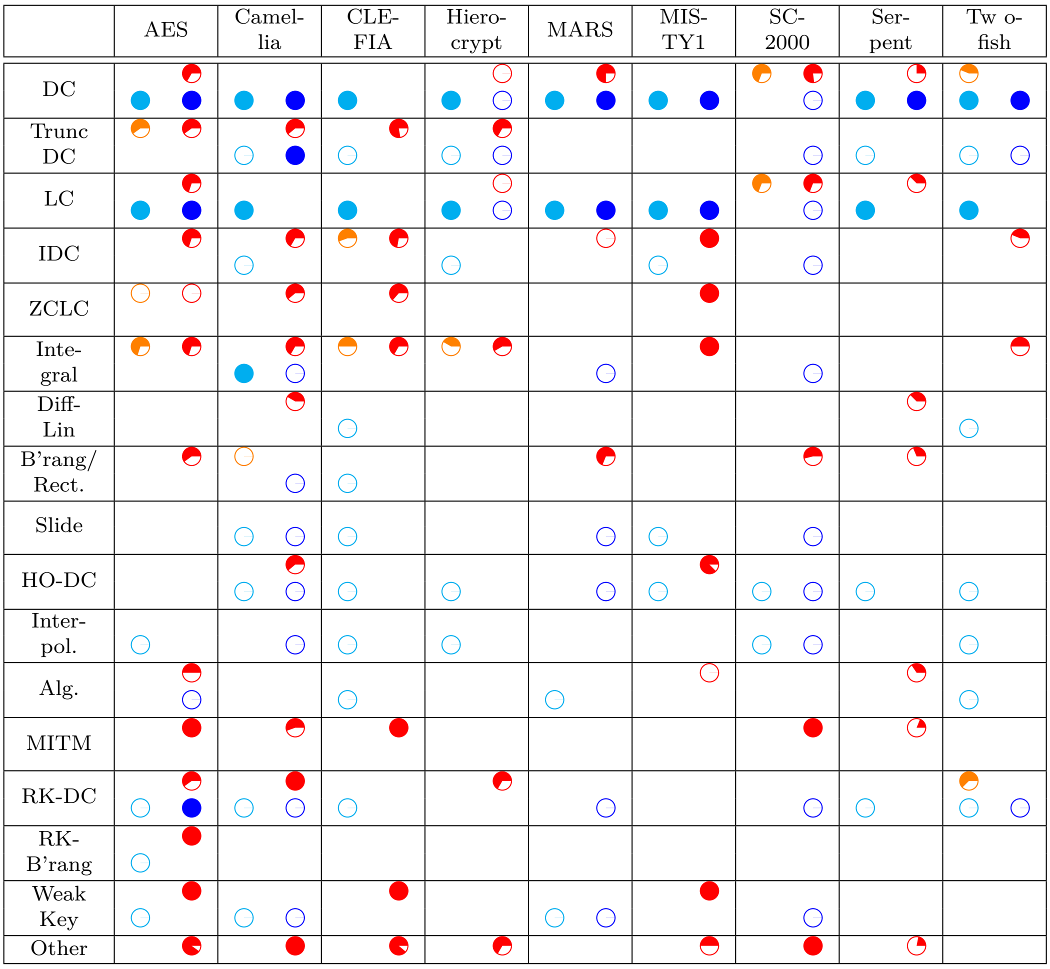
[1] Much of CIPHERUNICORN's documentation and evaluation was done in Japanese, so we were unable to include it.

Table 5: Summary of claims made in the security evaluation literature for nine popular SBox-based block ciphers from cryptographic competitions. In each cell, orange/ red dots indicate cryptanalysis work while cyan/blue dots indicate claims of security. In both cases, the color depends on whether the claims were made by the authors or in subsequent literature, respectively. Each dot's shading represents the gravity of the claim made (see Section 5.1 for details).



	AES	Camellia	CLEFIA	Hierocrypt	MARS	MISTY1	SC-2000	Serpent	Tw ofish
DC	◕ ● ●	● ●	●	○ ● ○	◕ ● ●	● ●	◕ ◕ ○	◔ ● ●	◔ ● ●
Trunc DC	◑ ◑	◑ ○ ●	◕ ○	◕ ○ ○			○	○	○ ○
LC	◕ ● ●	●	●	○ ● ○	● ●	● ●	◕ ◕ ○	◔ ●	●
IDC	◕	◕ ○	◑ ◕	○	○	● ○	○		◑
ZCLC	○ ○	◑	◑			●			
Integral	◕ ◕	◕ ● ○	◑ ◕	◔ ◑	○	●	○		◑
Diff-Lin		◔	○					◔	○
B'rang/ Rect.	◑	○ ○	○		◕		◑	◔	
Slide		○ ○	○		○	○	○		
HO-DC		◑ ○ ○	○	○	○	◕ ○	○ ○	○	○
Interpol.	○	○	○	○			○ ○		○
Alg.	◑ ○		○		○	○		◔	○
MITM	●	◑	●				●	◔	
RK-DC	◑ ○ ●	● ○ ○	○	◕	○		○	○	◑ ○ ○
RK-B'rang	● ○								
Weak Key	● ○	○ ○	●		○ ○	●	○		
Other	◕	●	◕	◕		◑	●	◔	

5.1 Breadthwise Study of Security Evaluations

In Table 5, we summarize the claims made for each scheme with respect to each of our cryptanalytic techniques. In each cell, we include up to four colored dots. Orange and red dots indicate cryptanalytic works by the authors and subsequent literature, respectively. The amount that the dot is colored in indicates the proportion of the full cipher that the most successful attack addresses. (e.g. ◔ would indicate that the cryptanalytic technique leads to a key-recovery attack on a variant of the cipher with a quarter of the rounds.) Note that an empty dot (i.e. ○ or ○) indicates that concerns have been raised about the scheme's security but no key-recovery attack has emerged (e.g. a distinguisher was found but not extended to a full attack). Cyan and blue indicate claims of security that have been made about the cipher. In particular, a filled dot (i.e. ● or ●) indicates a **proof of resistance** to the attack. This includes any formal analysis of why the cryptanalytic technique cannot be applied to the full cipher. On the other hand, an empty dot indicates a **claim of resistance** to the attack. This include all other claims that the scheme "should" resist the attack in question. This usually takes the form of heuristic arguments which explain why the attack would be "difficult to mount".

Since this is only intended as a broad overview for us to draw conclusions from, the table below simplifies the literature in a number of ways. First, in schemes with multiple key-sizes, the security claims apply to all variants and attacks reflected are the best performing one (in terms of the proportion of rounds) across all key sizes. Second, we include any attack that achieves a better time complexity than exhaustive search (i.e. they need not be "practical attacks"). Among works applying the same attack to the same scheme, we present only the maximal number of rounds for which a successful attack has been presented. Third, the rows associated to specific cryptanalytic techniques only consider attacks that work on the majority of keys. We gather all results that work on particular small classes of weak keys under the "Weak Key" row. Fourth, we acknowledge that works under the "defender POV" may present proofs in a variety of models, under very specific and different conditions. For example, some analyses are confined to certain special cases of the attacks or subclasses of differentials, or it may idealize portions of the scheme (e.g. SBoxes). For the sake of analysis, we generously permit all of these as "proofs" in the below table.

Due to the vast amount of literature covered by this table, we defer all citation details for Table 5 to after our analysis of the table. In Section 5.2 we provide some details on each scheme and links to their documentation. We also list all security claims and attacks that we are aware of for each scheme that were aggregated to form Table 5.

Discussion on Table 5. We acknowledge that there are many factors influencing how the research community as a whole handles the security evaluations of popular ciphers. However, we believe that there are still some interesting observations that can be drawn from Table 5. We now highlight some of these trends, and suggest some possible interpretations and avenues for future work that come out of them.

We observe that each cell where key-recovery attacks exist from both the authors and the subsequent literature, the latter always demonstrates improvement over the former. In Table 5, there is an average difference of 1.07 rounds, or 8.25% of the number of rounds in each full cipher. Additionally, we note that for each cryptanalytic attack from the literature presented in the table (i.e. the 54 non-empty dots in the top-right of cells) represents between 1 and 14 works, with an average of 3.69 works. These sequences of work steadily improved the rounds and complexities of the attack in question over the course of time. One takeaway that a scheme designer might draw from this is that *round-reduced cryptanalysis inevitably improves over time.* Therefore, if they use round-reduced cryptanalytic results of their own to justify their scheme's security against that form of cryptanalysis, they should incorporate a substantial number of buffering rounds to allow for cryptanalytic improvements over time. We believe that this buffer size is scheme-dependent, and may relate to the diffusion characteristics of the underlying round functions. This may constitute an interesting area for future work.

Now let's look at the relationship between the scheme's designers' security assurances (i.e. cyan dots) and cryptanalytic success (i.e. red dots). We note that the majority of the proofs (i.e. ●) concern the full cipher, so the presence of an attack does not invalidate the proof. For this analysis we only consider "significant" cryptanalytic efforts, which we define as breaking at least half of the rounds of the full cipher. From this, we can note that for all cells with assurances of security (i.e. ●/○), only 16 out of 55 (29.09%) have seen substantial attacks (i.e. red dot between ◓ and ●). This suggests a correlation between the cryptanalytic considerations during the design process and the security of the resultant cipher. This can be seen as evidence that *security evaluation via cryptanalytic techniques works.*

We also note that in the cases where an assurance of security (i.e. ●/○) was given but a full break was found (i.e. ●), it occurs when the assurance was done using heuristic techniques instead of a formal proof. We believe that this speaks to the *value of formal* *proof frameworks for deterring cryptanalysis* and believe that future work developing such would be well-received by cipher designers (much like Matsui's formalization of LC and DC [Mat95] which have been extended to the proof frameworks used by almost all our nine ciphers).

We can also draw some conclusions by looking at each scheme as its own case study. We note that one should be careful not to overgeneralize using Table 5. For example, AES having the "most red dots" is more likely to be a function of the popularity and visibility of this scheme, rather than an indicator that AES is the weakest cipher of the nine presented. However, our results provide at least anecdotal evidence that *discrepancies in security between comparable scheme may emerge over the course of time.* For example, SERPENT and MISTY1 were both proposed in 1998 with a very similar list of security assurances and comparable visibility (in terms of citations). However, since then, MISTY1 has been attacked much more successfully than SERPENT. While multiple cryptanalytic techniques have seen success when applied to full or almost-full-round MISTY1, SERPENT has not even seen an attack for more than 12 out of its 32 rounds. We see this as evidence that *scheme selection should not be rushed*, and that it may even be valuable to revisit the results of past selections and review cryptanalytic results that have emerged since then (similar to what CRYPTREC did in 2013 when they revisited their selected schemes and reorganized them into different tiers).

Reflections from Survey Process. At the close of this section, we make a couple final observations from the entire survey process that might be relevant to future work.

First, we feel that the study of block cipher cryptanalysis, especially from the POV of the attacker, is a very detailed-oriented and fiddly discipline. Great care must be taken to ensure the correctness, especially since most of the attacks exceed a practical amount of resources and cannot be verified via an implementation. Further evidence of this can be seen in the errors that have been pointed out in published cryptanalytic work which completely void the correctness of the attacks [Sch02, LK07, BNS14]. To address this, future work may consider formalizing adversarial models and a common syntax for classes of cryptanalytic attacks (perhaps extending our work in Section 3) to ease comparisons between different schemes, or even frameworks that simplify the verification of key-recovery attacks.

Second, it is worth noting that this area of research is both mature and vast. Our SoK covered a large portion of the literature out there, but we believe much more can be done to reorganize the area. In particular, future work may look to systemize cryptanalysis using side channels, alternate adversarial models, other block cipher types (e.g. ARX), or studying a wider breadth of schemes (e.g. authenticated encryption schemes from CAESAR [cae19]).

5.2 Summary of Cryptanalytic Results Against Competition Schemes.

Overview. Below we list works from the literature that we compiled to generate Table 5 in Section 5. For each of the nine schemes, we use two tables to capture the cryptanalytic works on that scheme and the security analyses of the scheme (respectively). We use the same color-coding as we did in Table 5 to differentiate between attacks/security claims and claims by the authors/subsequent work.

These works were all considered when constructing Table 5 with the exception of the algebraic XSL attacks (indicated with a † symbol) since the technique is controversial and has been questioned by many including [Sch02, LK07]. As discussed in Section 5, we consider an attack successful if it is able to break the cipher variant with lower time complexity than an exhaustive search. And for security claims, we distinguish between claims of security backed by rigorous mathematical proofs (i.e. which would likely indicate that applying the attack would be unproductive/impossible in a general sense) from those which indicate a likelihood of security (e.g. pointing out some design feature of the cipher which would likely resist the attack in question). Of course, this distinction at times requires us to make a subjective judgement call and future work could look into more nuanced ways to perform this classification.

Finally, as one might expect, not every piece of literature falls nicely into one of the cryptanalytic techniques we discussed. In our tables below, we try our best to faithfully represent techniques used. When compiling into Table 5, we gently relax some of the attack definitions to include closely related attack types, so that we can group as many attacks as we can under the list of major cryptanalytic techniques. We were able to group 154 out of 175 (88%) works in this way. Additionally, when cryptanalytic works present attacks on multiple similar cipher variants using the same cryptanalytic technique we only reflect the one which breaks the largest number of rounds.

AES (128-BIT RJINDAEL). Rjindael is an SPN cipher which won the NIST AES competition. AES was also selected among the recommended candidates in CRYPTREC and NESSIE. It has a 128-bit block, 128/192/256-bit keys, and 10/12/14 rounds, respectively.

In our study, we studied the cipher and claims given by the authors in the Rijndael specification document [AES01] and AES proposal [DR03], and compared them to those found in mainstream cryptography journals/conferences.

We summarize the works presenting key-recovery attacks on various reduced round variants of AES in Fig. 3. We also present security claims associated to AES in Fig. 4.

CAMELLIA. This is a GFN cipher that is recommended by CRYPTREC and NESSIE. Camellia has a 128-bit block, 128/192/256-bit keys, and 18/24/24 rounds, respectively.

In our study, we studied the cipher and claims given by the authors in their paper [AIK+01], the Camellia specification document [AIK+00] and supporting document [NC02], and compared them to those found in mainstream cryptography journals/conferences.

We summarize the works presenting key-recovery attacks on various variants of Camellia in Fig. 5. In addition to having reduced rounds, the works may also remove FL layers or whitening rounds from their variants. Since these significantly impact security, we indicate such variants in Fig. 5 as well. We also present security claims associated to Camellia in Fig. 6.

CLEFIA. CLEFIA is a GFN cipher recommended in CRYPTREC. CLEFIA has a 128-bit block, 128/192/256-bit keys, and 18/22/26 rounds, respectively.

In our study, we studied the cipher and claims given by the authors in their paper [SSA+07] and self-evaluation document[Son07], and compared them to those found in mainstream cryptography journals/conferences.

We summarize the works presenting key-recovery attacks on various variants of CLEFIA in Fig. 7. In addition to having reduced rounds, the works may also the whitening rounds from their variants. However, we believe that those attacks can be extended to include the key whitening rounds via the techniques used by [LJWD15]. We also present security claims associated to CLEFIA in Fig. 8.

HIEROCRYPT-L1. This is a recursively defined SPN cipher recommended in CRYPTREC. It has a 64-bit block and 128-bit keys. In the literature, this is sometimes described to have 6 rounds and other times as having 12 (SBox) layers. Below, we present all results in rounds for easy comparison. CRYPTREC also recommended the Hierocrypt-3 cipher, which has a very similar design but has a 128-bit block.

In our study, we studied the cipher and claims given by the authors in their paper [OMSK01], specification document [Cor01b] and self-evaluation document[Cor01a], and compared them to those found in mainstream cryptography journals/conferences.

We summarize the works presenting key-recovery attacks on various reduced round variants of Hierocrypt-L1 in Fig. 9. We also present security claims associated to Hierocrypt-L1 in Fig. 10.

Attack	# Rounds (by key len.)			Citation
	128-bit	192-bit	256-bit	
Trunc. DC	6	6	6	[AES01, DR03]
Integral	7	7	7	[AES01, DR03]
DC-MITM	4	4	4	[BDD+12]
DC		8	9	[Sas10]
Trunc. DC	6			[BGL19]
LC	7	7	7	[GM00]
IDC	5	5	5	[BK00]
IDC	6	6	6	[CKK+02]
IDC		7	7	[Pha04]
IDC	7			[BA07]
IDC	7	7	8	[ZWF07]
IDC	7	7	8	[LDKK08]
IDC	7			[MDRMH10]
IDC	7			[BLNS18]
IDC	7			[LP21]
Integral	6	6	6	[BK00]
Integral	6	7	7	[Tun12]
Integral	7	7	7	[L+00]
Integral	7	8	8	[FKL+01]
B'rang	6	6	6	[Bir04]
Alg. (Multiple-of-8)			7	[GRR17, BDK+18, BCC19]
Alg. (XSL)†	10	12	14	[CP02]
MITM		7	8	[DS08a]
MITM	7	7	8	[DTÇB09]
MITM	7	8	8	[DTÇB09]
MITM		8		[WLH10]
MITM		8	8	[DF14]
MITM	7	8	9	[DFJ13]
MITM		9	9	[LJW15]
MITM (Biclique)	10	12	14	[Bog12]
MITM (Biclique)	10	12	14	[BKR11a, GS13, BCGS15] [AFL+14, CNV13, TW15]
RK-DC	6			[SGL+17]
RK-DC		7	7	[ZWZF07]
RK-DC		8		[JD04]
RK-B'rang (Rect)		8		[HKLP05]
RK-B'rang		9		[GL08]
RK-B'rang (Rect)		9	10	[BDK05b, ZWZF07]
RK-B'rang (Rect)		10	10	[KHP07]
RK (Amp.) B'rang		12		[BK09]
RK-B'rang			14	[BK09]
RK-IDC	7	8	8	[ZWZF07]
RK-IDC		8	8	[BDK06]
RK-IDC		8	8	[ZWZF07]
RK-Integral	9	9	9	[FKL+01]
RK Diff-Lin		8		[ZZWF07]
Weak Key (RK-DC)	10	12	14	[BKN09]
Weak Key (RK B'rang)			10	[FGL09]
Rel. Subkey-DC			11	[BDK+10]
Diff. Enum.		8	8	[DKS10]
Imp. Polytopic	5	5	5	[Tie16]
Yoyo	5	5	5	[RBH17]
Mixture DC	6			[Gra17, BCC19, Gra19]

Figure 3: Key-Recovery attacks on reduced round variants of AES whose full variants contain 10/12/14 rounds respectively. These are the works on AES cryptanalysis that we surveyed to construct Fig. 5. (With the exception of controversial results labeled †.)

Attack	Security Claim	Citation
DC	●: Full AES is secure against DC attacks	[AES01, DR03]
LC	●: Full AES is secure against LC attacks	[AES01, DR03]
Interpol.	○: Diffusion layer provides security	[AES01, DR03]
Weak Key	○: IDEA weak key class	[AES01, DR03]
RK-Attacks	○: Key schedule offers security	[AES01, DR03]
DC	●: Full AES is secure against DC attacks	[PSC+02]
DC	○: Reduced round probability bound	[DR06]
LC	●: Full AES is secure against LC attacks	[PSC+02]
DC/LC	○: MILP analysis of ShiftRows' role in resisting DC/LC	[BJL+15]
IDC/ZCLC	○: No generic proof of without considering SBox details	[SLG+16]
Alg.	○: Resistance against known algebraic cryptanalysis	[Gho17]
Alg.	○: Simple algebraic presentations casts doubt on security	[FSW01, MR02] [BPW06]
RK-DC	●: Proof of active SBoxes in AES-128 in RK-setting	[KLPS17]
RK-DC	○: No generic proof of without considering MDS/SBox details. 9 round distinguisher has been found.	[FJP13]
Weak Key	○: Developed new framework which yields weak-key classes	[GLR+19]
Exchange	○: 6 round distinguisher has been found.	[BR19b, Bar19]

Figure 4: Security claims in the literature about AES' cryptanalysis. These are the AES analyses that we surveyed to construct Fig. 5.

MARS. This is a GFN cipher that was an AES finalist. It has a 128-bit block and 16 rounds, and allows the user to use between 128 to 448 key bits. However, since it was an AES finalist, it is often assumed to have 128, 192 or 256-bit keys.

In our study, we studied the cipher and claims given by the authors in their paper [BCD+99] and specification document [BCD+98], and compared them to those found in mainstream cryptography journals/conferences.

We summarize the works presenting key-recovery attacks on various reduced round variants of MARS in Fig. 11. We also present security claims associated to MARS in Fig. 12.

MISTY1. This is a GFN cipher that recommended by CRYPTREC and NESSIE. It has a 64-bit block, 128-bit key and a variable number of rounds (recommended: 8). KASUMI [rGPPG07], a popular cipher used in mobile telecommunications, is a variant of MISTY1.

In our study, we studied the cipher and claims given by the authors in their paper [Mat97] and supporting document [Mat00], and compared them to those found in mainstream cryptography journals/conferences.

We summarize the works presenting key-recovery attacks on various variants of MISTY1 in Fig. 13. In addition to having reduced rounds, the works may also remove some or all of the FL layers from their variants. In Fig. 13, the works indicated with a ✓ are those which consider any number of FL layers in their attacks, and those indicated with × considered none of them. We also present security claims associated to MISTY1 in Fig. 14.

SC2000. This is an SPN (by our definition) cipher recommended by CRYPTREC. It has a 128-bit block and 128/192/256-bit keys. SC2000 makes use of "I functions", "B functions" and "R functions", in a repeating IBIRR pattern with a trailing IBI for symmetry. In the original design, only the B and R functions were considered as "rounds", and the cipher was designed with 19/22/22 rounds (respectively). In subsequent literature, rounds are counted differently, with IBIRR being counted as a full round while IBI or RR are counted as half rounds. For consistency, we use the latter notation, meaning that SC2000 has 6.5/7.5/7.5 rounds (respectively).

In our study, we studied the cipher and claims given by the authors in their paper [SYY+02], and compared them to those found in mainstream cryptography journals/conferences.

Attack	# Rounds (by key len.)			FL	Whit-ening	Citation
	128-bit	192-bit	256-bit			
Trunc. DC	8			×	×	[LHL+02]
Trunc. DC	11	11	11	×	×	[SKI01]
Trunc. DC	11	12		✓	✓	[LJWD15]
IDC	12			×	×	[MSDB09]
IDC		10	11	✓	✓	[CJYW11]
IDC			15	×	×	[CJYW11]
IDC	11	12	14	✓	✓	[BL11]
IDC	10	11	12	✓	✓	[LCW11]
IDC		12	14	✓	×	[LCW11]
IDC	10	11	11	✓	✓	[LCJ11]
IDC		11	12	✓	✓	[LGL+11]
IDC	10	11	12	✓	✓	[LLG+12]
IDC	11	12		✓	✓	[LWFK12]
IDC		14	16	×	×	[LWFK12]
IDC		13	14	✓	×	[LGLL12]
IDC		13	14	✓	×	[Blo15]
IDC		14		✓	×	[JW16]
ZCLC		11	12	✓	×	[Bog12]
ZCLC	11	12		✓	✓	[BGW+14]
Integral	6			×	✓	[HQ01]
Integral			9	✓	×	[YPK02, LWFK12]
Integral	9		10	✓	✓	[LCF06]
Integral	9		11	×	×	[LCF06, LWFK12]
Integral	9		12	×	×	[LLF08, LWFK12]
Integral	10	12	12	×	×	[LWZZ11]
(MITM) Integral	10	11	12	✓	×	[LWKP12]
(MITM) Integral		14	16	×	×	[LWKP12]
Diff-Lin		9	10	×	×	[WF04]
HO-DC			11	×	×	[HSK03, LWFK12]
MITM			12	✓	✓	[CL12]
MITM	10	11	12	✓	×	[LWPF12]
MITM		12	13	✓	✓	[LJ14]
MITM	10	12	13	✓	✓	[DLJW15]
MITM (Biclique)	18	24	24	✓	✓	[Bog12]
RK-DC	18			×	×	[BN10]
Collision Searching	8	9	10	✓	✓	[WFC04]
Collision Searching	9	10	10	×	×	[WF03]

Figure 5: Key-Recovery attacks on reduced round variants of Camellia whose full variants contain 18/24/24 rounds respectively. These are the works on Camillia cryptanalysis that we surveyed to construct Fig. 5.

Attack	Security Claim	Citation
DC	●: Camellia is secure against DC attacks	[AIK+01, NC02]
Trunc. DC/LC	○: Found no attack on more than 10 rounds using [MT99, MSAK99] search methodology	[AIK+01, NC02]
LC	●: Camellia is secure against LC attacks	[AIK+01, NC02]
IDC	○: FL functions make IDC against full Camellia difficult	[AIK+01, NC02]
Integral/ interpol.	●: Searched for linear relations and proved no attack exists	[AIK+01, NC02]
B'rang	○: 8 round boomerang distinguisher found (no FL functions)	[AIK+01, NC02]
Slide	○: FL functions makes slide attack unlikely	[AIK+01, NC02]
HO-DC	○: High degree in SBox output makes HO-DC difficult	[AIK+01, NC02]
RK-DC	○: Key schedule makes RK-DC difficult	[AIK+01, NC02]
Weak Key	○: Key schedule makes equivalent key-classes unlikely	[AIK+01, NC02]
DC	●: No DC on more than 10 rounds	[BN12a]
DC/LC	○: No attacks on more than 10 rounds (no FL)	[SKA02]
Trunc. DC	●: No attacks on more than 11 rounds	[KM02]
Trunc. DC	●: No attacks on more than 7 rounds	[BN12a]
Integral	○: Integral less effective than trunc. DC	[CRY01a]
B'rang	○: "Approximately" 11 rounds will resist B'rang attack	[BN12a]
Slide/ Rotational	○: Structure not suited to these attacks	[BN12a]
HO-DC	○: High-degree SBox makes HO-DC difficult	[CRY01a]
Interpol.	○: Complex mathematical structure makes interpolation attack difficult	[CRY01a]
RK-DC	○: Structure makes these attack difficult	[CRY01a]
RK-DC	○: RK-DC (i.e. [BN10]) is infeasible	[BN12a]
Weak Key	○: Structure makes these attack difficult	[CRY01a]
Non-surjective	○: Structure makes these attack difficult	[CRY01a]
Mod n	○: Structure makes these attack difficult	[CRY01a]

Figure 6: Security claims in the literature about Camellia's cryptanalysis. These are the Camellia analyses that we surveyed to construct Fig. 5.

Attack	# Rounds (by key len.)			Whit-tening	Citation
	128-bit	192-bit	256-bit		
IDC	10	11	12	×	[SSA+07, Son07]
Integral	9	10	10	✓✗	[SSA+07, Son07]
Trunc. DC	14	14	15	×	[LJWD15]
IDC	12	13	14	✓	[WW07]
IDC	12	13	14	✓	[TTS+08b]
IDC	12	13	14	✓	[TTS+08a]
IDC	13			✓	[TSLL11]
IDC	13			✓	[MDS11]
IDC	13			✓	[BNS14]
ZCLC			13	✓	[BR11]
ZCLC		13	14	✓	[Bog12]
Multidim. ZCLC		14	15	✓	[BGW+14]
ZCLC		14	15	✓	[YC16]
Integral	12			✓	[SW13]
Integral	12	13	14	✓	[LWZ12]
Integral		14	15	✓	[YC16]
MITM (Biclique)	18	22	26	✓	[Bog12]
Weak Key (RK-DC)	18			✓	[ELN+14]
Imp. Diff-Lin	16			✓	[YLL13]
Improb. DC	13	14	15	✓	[Tez10]

Figure 7: Key-Recovery attacks on reduced round variants of CLEFIA whose full variants contain 18/22/26 rounds respectively. These are the works on CLEFIA cryptanalysis that we surveyed to construct Fig. 5.

Attack	Security Claim	Citation
DC	●: CLEFIA is secure against DC attacks	[SSA+07, Son07]
Trunc. DC	○: Distinguisher search suggests unlikely beyond 9 round on CLEFIA variant	[SSA+07, Son07]
LC	●: CLEFIA is secure against LC attacks	[SSA+07, Son07]
Trunc. LC	○: Implied by above DC result	[SSA+07, Son07]
Diff-Lin	○: Distinguisher search suggests this is worse than DC/LC. 8 round distinguisher has been found.	[SSA+07, Son07]
B'rang	○: Distinguisher search suggests unlikely beyond 9 rounds	[SSA+07, Son07]
Amp. B'rang	○: Distinguisher search suggests unlikely beyond 9 rounds	[SSA+07, Son07]
Rectangle	○: Estimates characteristic probability to be low, even though 10 round distinguisher is likely	[SSA+07, Son07]
Slide	○: Unlikely due to round constants	[SSA+07, Son07]
HO-DC	○: Unlikely due to high-degree SBoxes	[SSA+07, Son07]
Interpol.	○: Unlikely since number of terms needed to express SBoxes are high	[SSA+07, Son07]
Alg. (XSL)†	○: Estimates resources for XSL attack are impractical†	[SSA+07, Son07]
RK-DC	○: Probability estimates imply this is unlikely	[SSA+07, Son07]
Related cipher	○: Unlikely due to round constants	[SSA+07, Son07]
Collision	○: Suggests that collision techniques [GM00] may slightly improve integral attacks	[SSA+07, Son07]
χ^2	○: Unlikely since there are no useful correlations like those used against RC6 [Vau96, KM01]	[SSA+07, Son07]

Figure 8: Security claims in the literature about CLEFIA's cryptanalysis. These are the CLEFIA analyses that we surveyed to construct Fig. 5. (With the exception of controversial results labeled †.)

Attack	# Rounds	Citation
Integral	2.5	[OMSK01, Cor01a]
Trunc. DC	4	[ATY15]
Integral	3.5	[BRN+02]
RK-DC	4	[TMA14]
RK-IDC	4	[TMA14]

Figure 9: Key-Recovery attacks on reduced round variants of Hierocrypt-L1 whose full variant contains 6 rounds. These are the works on Hierocrypt-L1 cryptanalysis that we surveyed to construct Fig. 5.

Attack	Security Claim	Citation
DC	●: Full Hierocrypt-L1 is secure against DC attacks	[OMSK01, Cor01a]
Trunc. DC	○: Unlikely on more than 2.5 rounds	[OMSK01, Cor01a]
LC	●: Full Hierocrypt-L1 is secure against LC attacks	[OMSK01, Cor01a]
IDC	○: Hierocrypt design provides more resistance than AES	[OMSK01, Cor01a]
Integral	○: Hierocrypt design provides more resistance than AES	[OMSK01, Cor01a]
HO-DC	○: Unlikely due to high algebraic degree	[OMSK01, Cor01a]
Interpol.	○: Simple applications were ineffective	[OMSK01, Cor01a]
Non-Surjective	○: Unlikely due to cipher structure	[OMSK01, Cor01a]
Mod n	○: Unlikely due to cipher structure	[OMSK01, Cor01a]
χ^2	○: Unlikely due to cipher structure	[OMSK01, Cor01a]
DC	○: Provide upper bounds on security against DC	[OSSK01]
DC	○: Provide evidence that six rounds may not be enough	[Vau00a]
Trunc. DC	○: Unlikely due to cipher structure	[Vau00a]
LC	○: Provide upper bounds on security against DC	[OSSK01]
LC	○: Provide evidence that six rounds may not be enough	[Vau00a]

Figure 10: Security claims in the literature about Hierocrypt-L1's cryptanalysis. These are the Hierocrypt-L1 analyses that we surveyed to construct Fig. 5.

Attack	# Rounds (by key len.)			Citation
	128-bit	192-bit	256-bit	
DC			12	[GKL+11]
Amp. B'rang			11	[KKS01]

Figure 11: Key-Recovery attacks on reduced round variants of MARS whose full variants all contain 16 rounds. These are the works on MARS cryptanalysis that we surveyed to construct Fig. 5.

Attack	Security Claim	Citation
DC	●: MARS is secure against DC attacks	[BCD+99, BCD+98]
LC	●: MARS is secure against LC attacks	[BCD+99, BCD+98]
Alg.	○: Unlikely since it is not a group	[BCD+99, BCD+98]
Weak Key	○: Unlikely due to key expansion	[BCD+99, BCD+98]
Equiv. Keys	○: Unlikely due to key expansion	[BCD+99, BCD+98]
DC	●: MARS is secure against DC attacks	[CRY01b]
LC	●: MARS is secure against LC attacks	[CRY01b]
LC	○: Several works call into question the LC analysis [KR00, RY00, BCDM01], but no practical attack	[CRY01b]
IDC	○: 8 round distinguishers have been found	[BF00a]
Integral	○: Applies to MARS, but unlikely to exceed six rounds	[CRY01b]
Slide	○: Unlikely due to cipher structure	[CRY01b]
HO-DC	○: Unlikely due to high-degree SBox	[CRY01b]
RK-DC	○: Unlikely due to complex key schedule	[CRY01b]
Weak Key	○: Unlikely due to complex key schedule (MARS was changed to address weakness identified by [Saa99])	[CRY01b]
Non-Surjective	○: Unlikely due to cipher structure	[CRY01b]
Mod n	○: Unlikely due to cipher structure	[CRY01b]
Statistical	○: 8 rounds can be distinguished using "Book Stack" test	[Pes06]

Figure 12: Security claims in the literature about MARS' cryptanalysis. These are the MARS analyses that we surveyed to construct Fig. 5.

Attack	# Rounds	# FL	Citation
Slicing/ IDC	4	✓	[Küh02]
IDC	4	✓	[Küh01]
IDC	6	×	[Küh01]
IDC	6	✓	[LKKD08]
IDC/ Slicing	6	✓	[DK08]
IDC/ Slicing	7	×	[DK08]
IDC	7	✓	[JL12]
Multidim. ZCLC	7	✓	[YC14]
Integral	5	✓	[KW02]
Integral	6	✓	[SL09]
Integral	8	✓	[Tod15a]
Integral	8	✓	[Bar15a]
HO-DC	5	×	[THK99]
HO-DC	5	×	[BF01]
HO-DC	6	✓	[THSK08]
HO-DC	7	×	[THSK08]
HO-DC	7	✓	[TSSK09]
HO-DC	7	✓	[Bar15b]
Weak Key (RK-DC/ RK-B'rang)	8	✓	[LYW13]
Collision	4	✓	[Bih97, Küh01]

Figure 13: Key-Recovery attacks on reduced round variants of MISTY1 whose full variant is "recommended" to have 8 rounds. These are the works on MISTY1 cryptanalysis that we surveyed to construct Fig. 5.

Attack	Security Claim	Citation
DC	●: MISTY1 is secure against DC attacks	[Mat97, Mat00]
LC	●: MISTY1 is secure against LC attacks	[Mat97, Mat00]
IDC	○: Unlikely due to FL functions	[Mat97, Mat00]
Slide	○: Unlikely due to FL functions. (For variant with no FL, attack is slower than exhaustive.)	[Mat97, Mat00]
HO-DC	○: Unlikely due to algebraic structure and FL functions	[Mat97, Mat00]
DC	●: MISTY1 is secure against DC attacks	[LLSS10]
LC	●: MISTY1 is secure against LC attacks	[LLSS10]
IDC	○: Reduced round IDC likely, since multi round distinguishers exist	[LLSS10]
Integral	○: Reduced round Integral likely, since multi round distinguishers exist	[LLSS10]
HO-DC	○: SBox weakness enables the attacks by [THK99, BF01]	[CV02]
HO-DC	○: Reduced round distinguishers may yield HO-DC attacks	[Vau00b]
Alg.	○: Reduced round distinguishers may yield algebraic attacks	[Vau00b]
Weak Key	○: Subkey structure may yield weak keys	[Vau00b]
Generic Attacks	○: Minimum of 6 rounds required for security, even when assuming an idealized MISTY1	[NPT09, NPT10]

Figure 14: Security claims in the literature about MISTY1's cryptanalysis. These are the MISTY1 analyses that we surveyed to construct Fig. 5.

Attack	# Rounds (by key len.)			Citation
	128-bit	192-bit	256-bit	
DC	4.5	4.5	4.5	[SYY+02]
LC	4.5	4.5	4.5	[SYY+02]
DC	4.5	4.5	4.5	[RK01]
DC	4.5	4.5	4.5	[YSD02]
DC	5	5	5	[Lu10a]
LC	4.5	4.5	4.5	[YSD02]
B'rang	3.5	3.5	3.5	[BDK02c]
Rectangle	3.5	3.5	3.5	[BDK02c]
MITM (Biclique)	6.5	7.5	7.5	[Bog12]
Key Collision			7.5	[BN14, BN12b]

Figure 15: Key-Recovery attacks on reduced round variants of SC2000 whose full variants contain 6.5/7.5/7.5 rounds respectively. These are the works on SC2000 cryptanalysis that we surveyed to construct Fig. 5.

We summarize the works presenting key-recovery attacks on various reduced round variants of SC2000 in Fig. 15. We also present security claims associated to SC2000 in Fig. 16.

SERPENT. This is an SPN cipher that was an AES finalist. It has a 128-bit block, a key length of 256-bits (also 128 and 192 variants for the AES process), and 32 rounds.

In our study, we studied the cipher and claims given by the authors in their paper [BAK98] and specification document [ABK98], and compared them to those found in mainstream cryptography journals/conferences.

We summarize the works presenting key-recovery attacks on various reduced round variants of Serpent in Fig. 17. We also present security claims associated to Serpent in Fig. 18.

TWOFISH. This is an GFN cipher that was an AES finalist. It has a 128-bit block, any key length up to 256-bits (128/192/256 are the common lengths), and 16 rounds.

In our study, we studied the cipher and claims given by the authors in their specification document [SKW+98], and compared them to those found in mainstream cryptography journals/conferences.

We summarize the works presenting key-recovery attacks on various reduced round

Attack	Security Claim	Citation
HO-DC	○: Unlikely due to high degree polynomials	[SYY+02]
Interpol.	○: Unlikely due to variety and degree of algebraic structures	[SYY+02]
DC	○: Individual components seem to resist DC, but structure too complex to prove	[CRY01c]
Trunc. DC	○: Present evidence that Trunc. DC unlikely beyond 5 rounds	[CRY01c]
LC	○: Individual components seem to resist LC, but structure too complex to prove	[CRY01c]
IDC/RK-IDC	○: Unlikely due to high diffusion of word-based cipher	[BN12b]
Integral	○: Unlikely to do better than DC attacks	[CRY01c]
Slide	○: Unlikely due to key schedule	[CRY01c, BN12b]
HO-DC	○: Unlikely due to non-linearity of SBoxes	[CRY01c]
Interpol.	○: Unlikely due to design of SBoxes and B/R functions	[CRY01c]
RK-DC	○: Unlikely due to complex key schedule	[CRY01c]
Weak Key	○: Unlikely due to complex key schedule	[CRY01c]
Mod n	○: Unlikely to be applicable	[CRY01c]
Non-Surjective	○: Unlikely to be applicable	[CRY01c]
Rotational	○: Unlikely due to SBoxes and key schedule	[BN12b]

Figure 16: Security claims in the literature about SC2000's cryptanalysis. These are the SC2000 analyses that we surveyed to construct Fig. 5.

Attack	# Rounds (by key len.)			Citation
	128-bit	192-bit	256-bit	
DC	6	6	7	[KKS+00]
DC			8	[WW10]
Multi-DC	7	7	8	[WSTP12]
LC	10	11	11	[BDK02b]
LC	10	11	11	[CSQ07b]
LC	10	10	10	[Lu12, Lu10b]
LC/ Multi-LC	10	11	11	[CSQ07a, CSQ08]
Multi-LC	12	12	12	[NWW11]
Diff-Lin	10	11	11	[BDK03]
Diff-Lin	10	11	12	[DIK08]
Diff-Lin	10	11	12	[Lu12, Lu10b]
Diff-Lin	10	11	12	[TÖ14]
Diff-Lin			12	[BCD+21]
B'rang		8	8	[KKS+00]
Amp. B'rang		8	9	[KKS+00]
Amp. B'rang	8	8	8	[KKS01]
B'rang/Rect.	9	10	10	[BDK02c]
Rectangle	7	7	10	[BDK01]
Alg. (XSL)†	32	32	32	[CP02]
Alg. (Diff. Non-lin)			8	[WWH10]
Alg (Non-lin)	11	11	11	[MC13a, MC13b]
MITM			6	[KKS+00]
Improb. DC	7	7	7	[TTD14]

Figure 17: Key-Recovery attacks on reduced round variants of Serpent whose full variants all contain 32 rounds. These are the works on Serpect cryptanalysis that we surveyed to construct Fig. 5. (With the exception of controversial results labeled †.)

Attack	Security Claim	Citation
DC	●: Full Serpent is secure against DC attacks	[BAK98, ABK98]
Trunc. DC	○: Unlikely due to strong diffusion over many rounds	[BAK98, ABK98]
LC	●: Full Serpent is secure against LC attacks	[BAK98, ABK98]
HO-DC	○: Unlikely on more than 5 rounds, due to high-degree SBox	[BAK98, ABK98]
Alg. (Non-lin)	○: Unlikely to meaningfully improve upon LC due to large number of texts	[BAK98, ABK98]
RK-DC	○: Unlikely due to key schedule and multiple SBoxes	[BAK98, ABK98]
Statistical	○: Unlikely to be less complex than DC/LC	[BAK98, ABK98]
Partitioning	○: Unlikely to be less complex than DC/LC	[BAK98, ABK98]
DC	●: Serpent on 16 or more rounds is secure against DC	[WHC+00]
Multidim. LC	○: Multidimensional LC extends Multi-LC [CSQ07a, CSQ08]. 5 round distinguisher has been found.	[HCN08, CHN09]
Alg.	○: Non-linear order of SBox output bits misreported by authors, may yield algebraic attacks	[SAB09]

Figure 18: Security claims in the literature about Serpent's cryptanalysis. These are the Serpent analyses that we surveyed to construct Fig. 5.

Attack	# Rounds (by key len.)			Variant	Citation
	128-bit	192-bit	256-bit		
DC	5	5	5	×	[SKW+98]
DC	7	7	7	✓	[SKW+98]
RK-DC	10	10	10	✓	[SKW+98]
IDC	6	6	6	×	[Fer99]
IDC			6	✓	[Fer99]
IDC	7	7	7	×	[BF00b]
Integral	7	7	7	×	[Luc02]
Integral	8	8	8	✓	[Luc02]

Figure 19: Key-Recovery attacks on reduced round variants of Twofish whose full variants all contain 16 rounds. These are the works on Twofish cryptanalysis that we surveyed to construct Fig. 5.

variants of Twofish in Fig. 19. We also present security claims associated to Twofish in Fig. 20.

6 Conclusion

The block cipher design process is an intricate one, and it may be tricky to navigate the myriad of attacks and their conditions during security evaluation. In this paper, we presented a systemization of cryptanalysis of SBox-based block ciphers from a security evaluation standpoint. Additionally, we featured a unified common framework to present the attack techniques, generalizing distinguisher structures and consolidating respective formal and heuristic approaches to security evaluation. We also organized and compartmentalized the space of SBox-based block cipher attacks through graphical representations. Finally, we present a case study which draws conclusions about how security evaluation matures over time, with implications for future work.

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Attack	Security Claim	Citation
DC	●: Full Twofish is secure against DC attacks	[SKW+98]
Trunc. DC	○: Round function diffusion makes trunc. DC difficult	[SKW+98]
LC	●: Full Twofish is secure against LC attacks	[SKW+98]
Multiple LC	○: Unlikely since LC is unlikely	[SKW+98]
Generalized LC	○: Unlikely since statistical imbalances were not found	[SKW+98]
Diff-Lin	○: Unlikely due since DC component would cover most of cipher	[SKW+98]
HO-DC	○: No attacks on more than 6 rounds	[SKW+98]
Interpol.	○: Unlikely due to high algebraic degree of SBoxes	[SKW+98]
Alg. (Non-lin.)	○: Unlikely since LC is unlikely	[SKW+98]
RK-DC	○: Unlikely due to active SBoxes	[SKW+98]
RK-Slide	○: Attempted but unsuccessful	[SKW+98]
Partitioning	○: Attempted but unsuccessful	[SKW+98]
Partial Key	○: Unlikely due to strong key schedule	[SKW+98]
DC	●: 15 rounds will resist DC attack	[MR00]
Trunc. DC	○: Trunc. DC distinguishers [Knu00, MY00] does not necessarily extend to full attack	[Sch05]
RK-DC	○: Unlikely due to strong key schedule	[SKW+99]
RK-Slide	○: Unlikely due to strong key schedule	[SKW+99]
Equiv. Keys	○: Unlikely due to strong key schedule	[SKW+99]

Figure 20: Security claims in the literature about Twofish's cryptanalysis. These are the Twofish analyses that we surveyed to construct Fig. 5.

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