Symmetric lightweight primitives: (Design and) Cryptanalysis

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Outline

- Symmetric lightweight primitives
- Most used cryptanalysis
  - *Impossible Differential* Attacks
  - *Meet-in-the-middle*
  - Dedicated attacks
- Conclusions and remarks

Symmetric Lightweight Primitives

Lightweight Primitives

- Lightweight primitives designed for constrained environments, like RFID tags, sensor networks.

- Real need $\Rightarrow$ an enormous amount of proposals in the last years:

PRESENT, LED, KATAN/KTANTAN, KLEIN, PRINCE, PRINTcipher, LBLOCK, TWINE, XTEA, mCrypton, Iceberg, HIGHT, Piccolo, SIMON, SPECK, SEA, DESL...

- NIST competition to start around december 2018.

Cryptanalysis: Foundation of Confidence

Any attack better than the generic one
is considered a "break".

- Proofs on symmetric primitives need to make unrealistic assumptions.
- We need to perform an empirical measure of the security: cryptanalysis.

Lightweight Primitives

- Cryptanalysis of lightweight primitives:
  a fundamental task, responsibility of the community.

- Importance of cryptanalysis (especially on new proposals): the more a cipher is analyzed, the more confidence we can have in it...

- ...or know which algorithms are not secure to use.

Lightweight Primitives

- Lightweight: more 'risky' design, lower security margin, simpler components.
- Often innovative constructions: dedicated attacks
- Types of attacks: single-key/related-key, distinguisher/key-recovery, weak-keys, reduced versions.

On weakened versions

If no attack is found on a given cipher, what can we say about its robustness, security margin?

The security of a cipher is not a 1-bit information:

- Round-reduced attacks.
- Analysis of components.

$\Rightarrow$ determine and adapt the security margin.

On high complexities

When considering large keys, sometimes attacks breaking the ciphers might have a very high complexity far from practical *e.g.*. 2^{120} for a key of 128 bits.

Still dangerous because:

- Weak properties not expected by the designers.
- Experience shows us that attacks only get better.
- Other existing ciphers without the "ugly" properties.

- When determining the security margin: find the highest number of rounds reached.

Main Objectives of this talk

- Perform a (non-exhaustive) survey of proposals and their security status.
- Provide the intuition of the "most useful attacks" against LW ciphers.
- Conclusions and remarks (link with hash functions).

Survey of Proposals [1]

- *Feistel Networks - best external analysis*
  DESLX - none
  ITUbee - self-similarity (8/20r)
  LBlock - **imposs. diff.** (24/32r)
  SEA - none
  SIMON and SPECK - **imposs. diff.**, diff, 0-correl.
  XTEA - **mitm** (23/64r)
  CLEFIA - **imposs. diff.** (13/18r)
  HIGHT - 0-correlation (27/32r)
  TWINE - **mitm,imposs. diff.**,0-corr (25/36r)

[1] mainly from https://cryptolux.org/index.php/Lightweight_Block_Ciphers

Survey of Proposals

- *Substitution-Permutation Network*
  KLEIN - **dedicated attack** (full round)
  LED - EM generic attacks (8/12r, 128K)
  Zorro - diff. (full round)
  mCrypton - **mitm** (9/12r, 128K)
  PRESENT - mult. dim. lin. (27/31r)
  PRINTcipher - **invariant-wk** (full round)
  PRIDE - diff (18/20r)
  PRINCE - mult. diff (10/12r)
  Fantomas/Robin -none/**invariant-wk** (full round)

Survey of Proposals

- *FSR-based*
  KTANTAN/KATAN - **mitm** (153/254r)
  Grain - correl./ cube attacks (some full)
  Trivium - cube attacks (800/1152) -
  Sprout - guess-and-determine (full round)
  Quark -condit. diff (25%)
  Fruit - divide and conquer (full)
  Lizard - guess-and-det. (full)

Survey of Proposals

- *ARX*
  Chaskey - diff-lin (7/8r)
  Hight - 0-correl (27/32r)
  LEA - diff. (14/24r)
  RC5 - diff. (full round)
  Salsa20 - diff (8/20r)
  Sparx - **imposs. diff.** (15/24r)
  Speck - diff. (17/32r)

More Proposals

For more details, primitives, classifications, see:

State of the Art in Lightweight Symmetric Cryptography,
by Alex Biryukov and Leo Perrin
https://eprint.iacr.org/2017/511

Most Successful Attacks

Families of attacks

- Impossible differentials (Feistel)
- Mitm / guess and determine (SPN, FSR)
- Dedicated: (differential/linear...)

Impossible Differential Attacks

Classical Differential Attacks [BS'90]

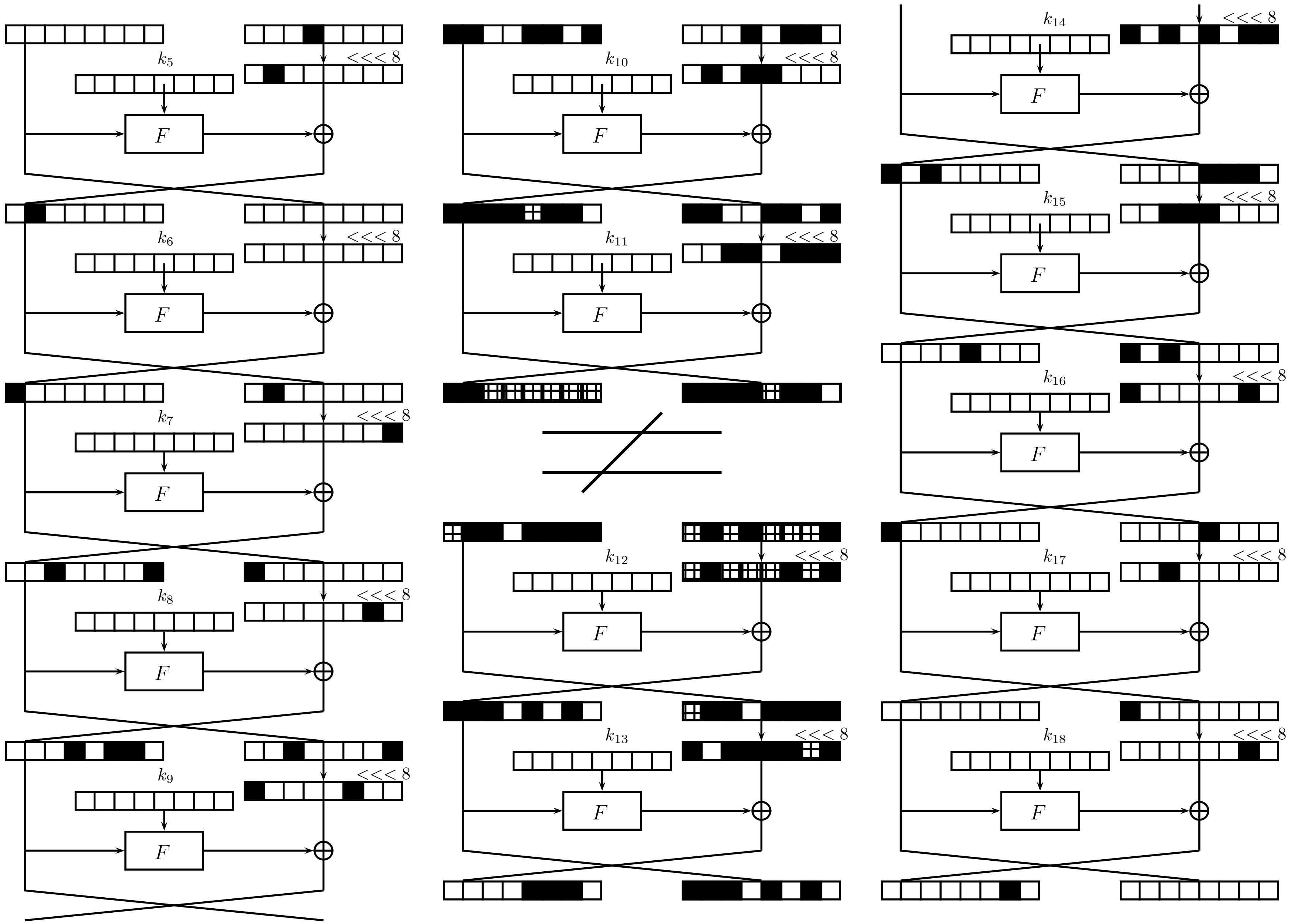
Given an input difference between two plaintexts, some output differences occur more often than others.

A differential is a pair (Δ_X, Δ_Y).

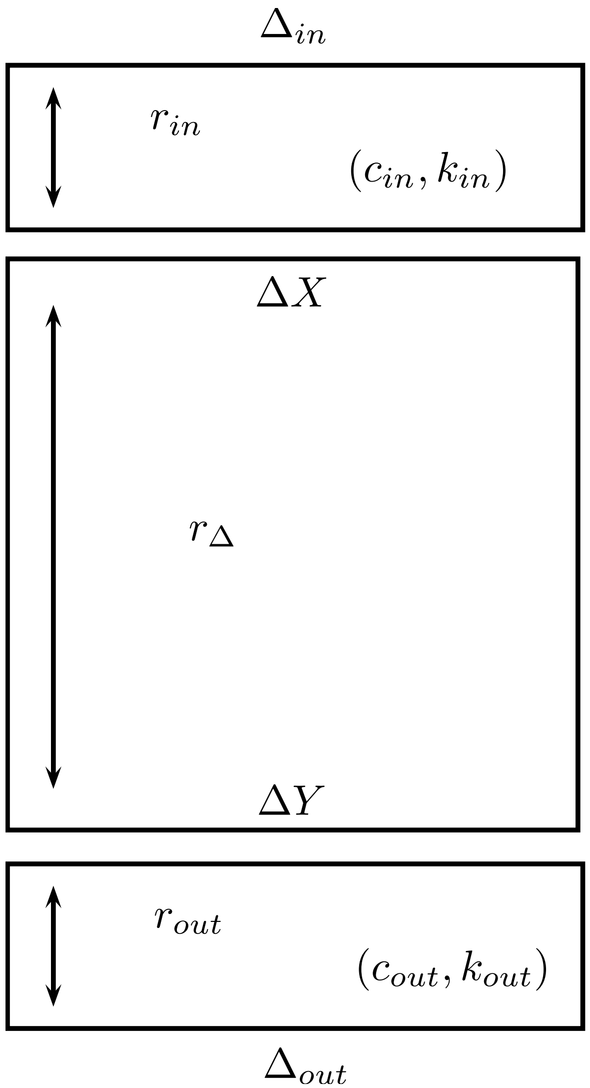
Impossible Differential Attacks [K,BBS'98]

- Impossible differential attacks use a differential with probability 0.
- We can find the impossible differential using the Miss-in-the-middle [BBS'98] technique.
- Extend it backward and forward $\Rightarrow$ Active Sboxes transitions give information on the involved key bits.
- Generic framework and improvements [BNPS14,BLNPS17]

Impossible differential: 14 rounds



Impossible Differential Attack



Discarding Wrong Keys

- Given one pair of inputs with Δ_{in} that produces Δ_{out},
- all the (partial) keys that produce ΔX from Δ_{in} and ΔY from Δ_{out} differ from the correct one.
- If we consider N pairs verifying $(\Delta_{in}, \Delta_{out})$ the probability of NOT discarding a candidat key is

$$(1 - 2^{-c_{in} - c_{out}})^N$$

For the Attacks to Work

We need, for a state size s and a key size $|K|$:

$$C_{data} < 2^s$$

and

$$C_{data} + 2^{|k_{in} \cup k_{out}|} C_N + 2^{|K| - |k_{in} \cup k_{out}|} P 2^{|k_{in} \cup k_{out}|} < 2^{|K|}$$

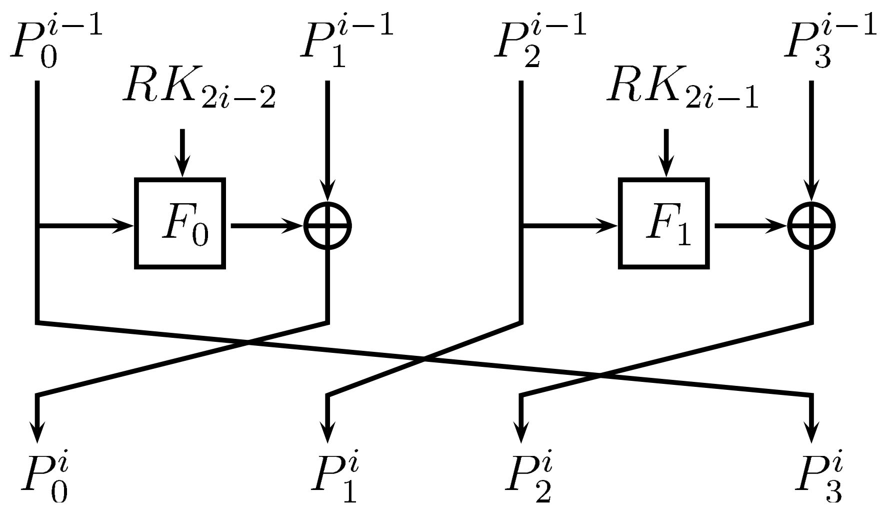
where C_{data} is the data needed for obtaining N pairs $(\Delta_{in}, \Delta_{out})$, C_N is the average cost of testing the pairs per candidate key (early abort technique [LKKD08]) and P is the probability of not discarding a candidate key.

Improvements from [BN-PS14,BLN-PS17]

- Multiple impossible differentials (related to [JN-PP13])
- Correctly choosing Δ_{in} and Δ_{out} (related to [MRST09])
- State-test technique (related to [MRST09])

Example: CLEFIA-128

- block size: $4 \times 32 = 128$ bits
- key size: 128 bits
- # of rounds: 18



Multiple Impossible Differentials

Formalize the idea of [Tsunoo et al. 08]:

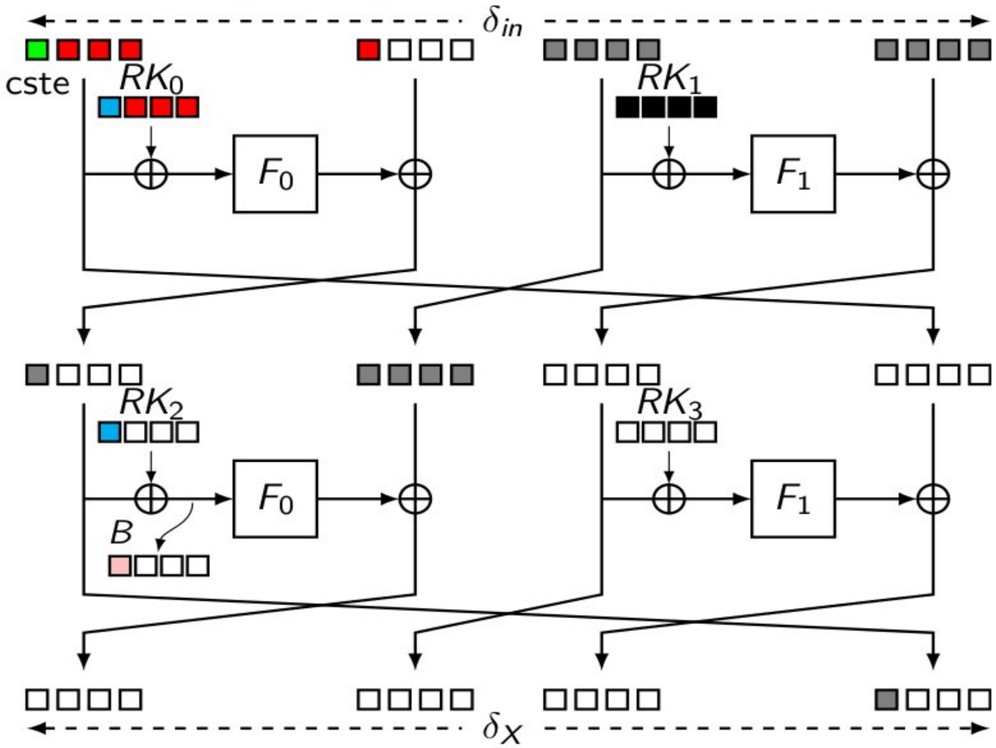
CLEFIA has two 9-round impossible differentials $((0,0,0,A) \not\rightarrow (0,0,0,B))$ and $((0,A,0,0) \not\rightarrow (0,B,0,0))$ when A and B verify:

A	B				
$(0,0,0,\alpha)$	$(0,0,\beta,0)$	or	$(0,\beta,0,0)$	or	$(\beta,0,0,0)$
$(0,0,\alpha,0)$	$(0,0,0,\beta)$	or	$(0,\beta,0,0)$	or	$(\beta,0,0,0)$
$(0,\alpha,0,0)$	$(0,0,0,\beta)$	or	$(0,0,\beta,0)$	or	$(\beta,0,0,0)$
$(\alpha,0,0,0)$	$(0,0,0,\beta)$	or	$(0,0,\beta,0)$	or	$(0,\beta,0,0)$

24 in total: $C_{data} = 2^{113}$ becomes $C_{data} = 2^{113}/24$

State Test Technique

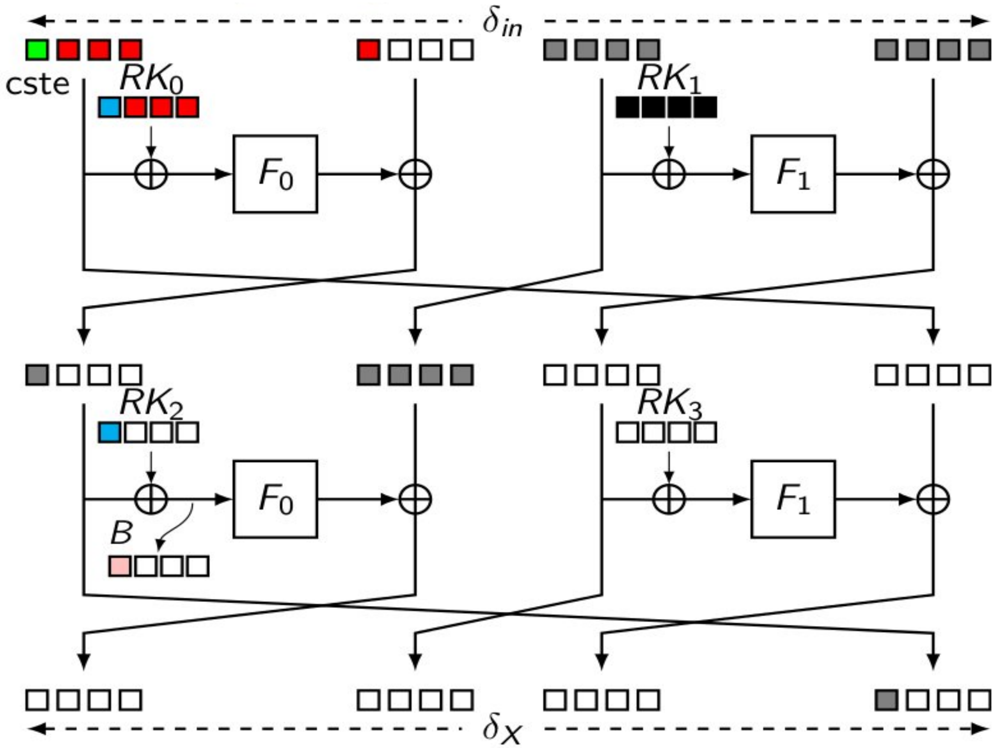
Reduce the number of key bits involved.



$B =$ ■ $\oplus S_0($■ $\oplus$ ■$) \oplus$ ■

State Test Technique

Reduce the number of key bits involved.



$$B' = \blacksquare \oplus S_0(\blacksquare \oplus \blacksquare) \quad (\text{with } B = B' \bigoplus \blacksquare)$$

$$|k_{in} \cup k_{out}| = 122 \text{ bits} \quad \Rightarrow \quad |k_{in} \cup k_{out}| = 122 - 16 + \underbrace{8}_{B'} \text{ bits}$$

Applications of Improved Impossible Diff

- CLEFIA: best attack on CLEFIA (13 rounds).
- Camellia: Improved best attacks for Camellia.
- AES: attacks comparable with best mitm ones (7 rounds).
- LBlock: best attack (on 24 rounds).

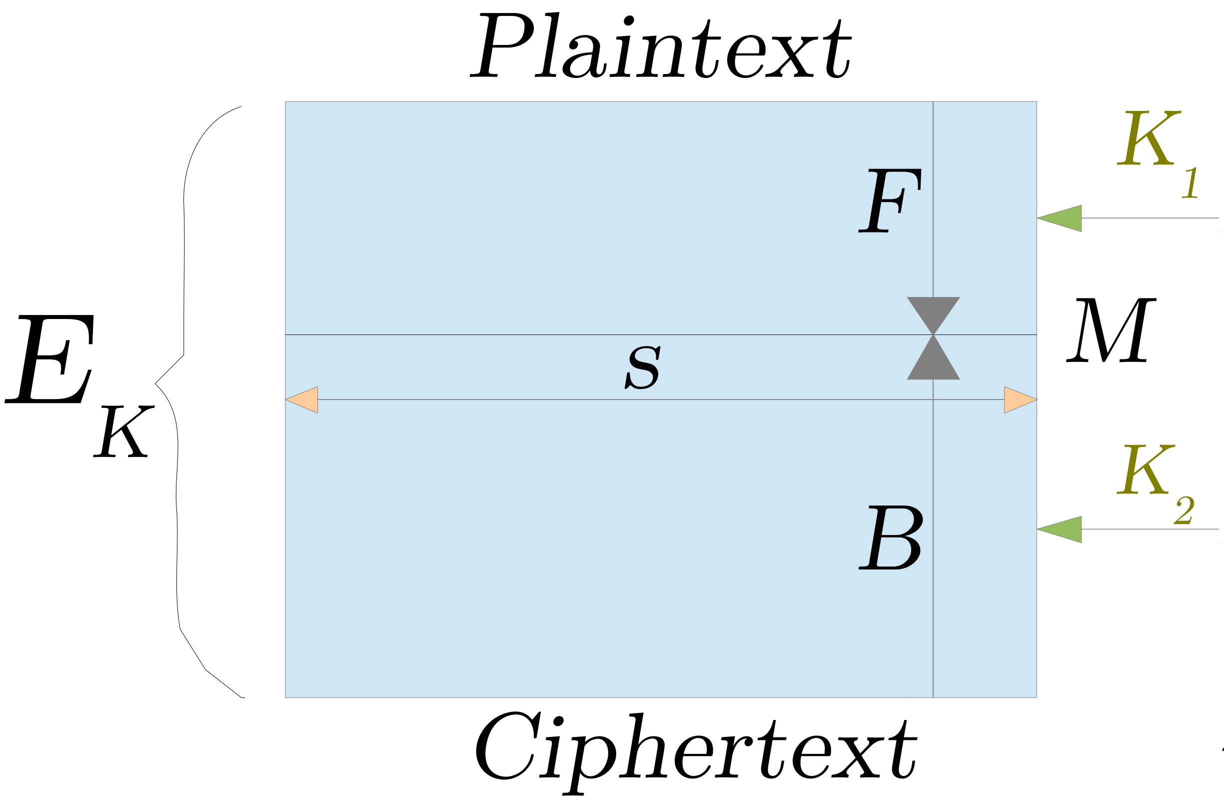
Meet-in-the-middle attacks

Meet-in-the-Middle Attacks

- Introduced by Diffie and Hellman in 1977.

- Largely applied tool.
- Few data needed.
- Many improvements: partial matching, bicliques, sieve-in-the-middle...

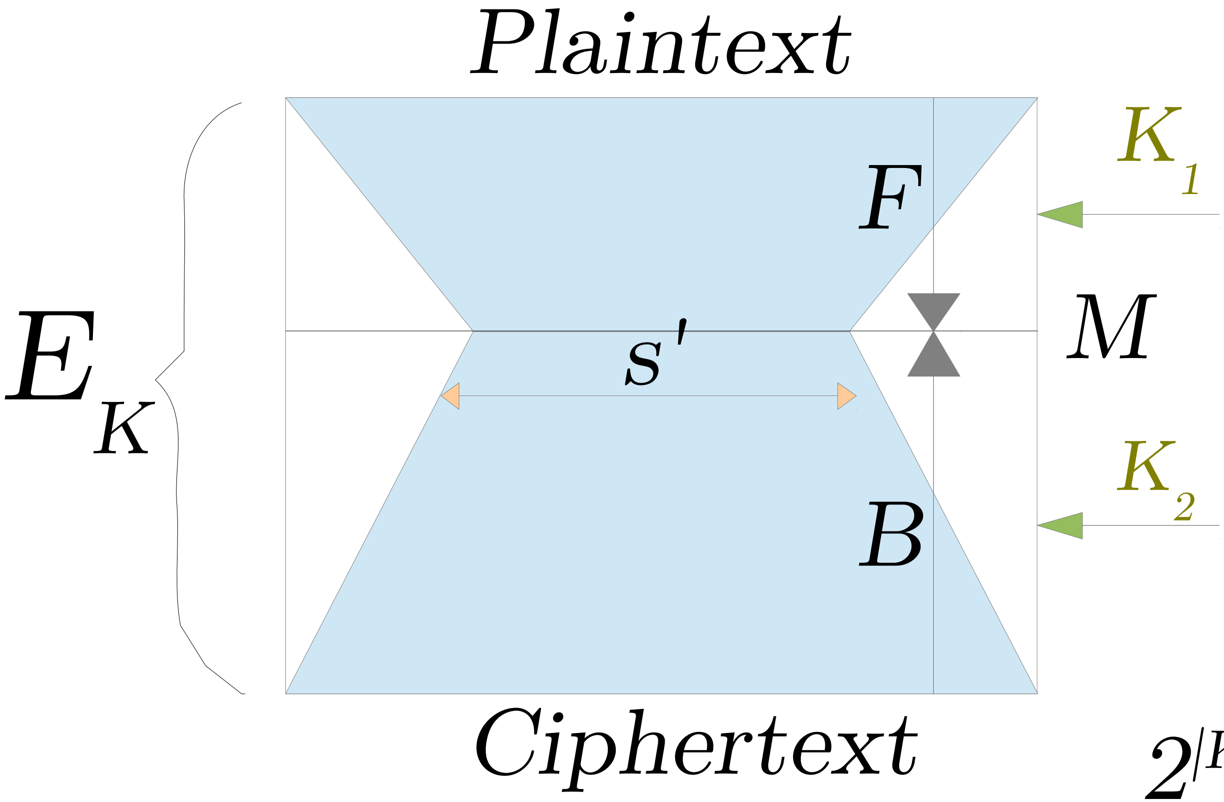
Meet-in-the-Middle Attacks [Diffie Hellman 77]



$K = K_1 \cup K_2$

$$2^{|K_1|} + 2^{|K_2|} + 2^{|K|-s}$$

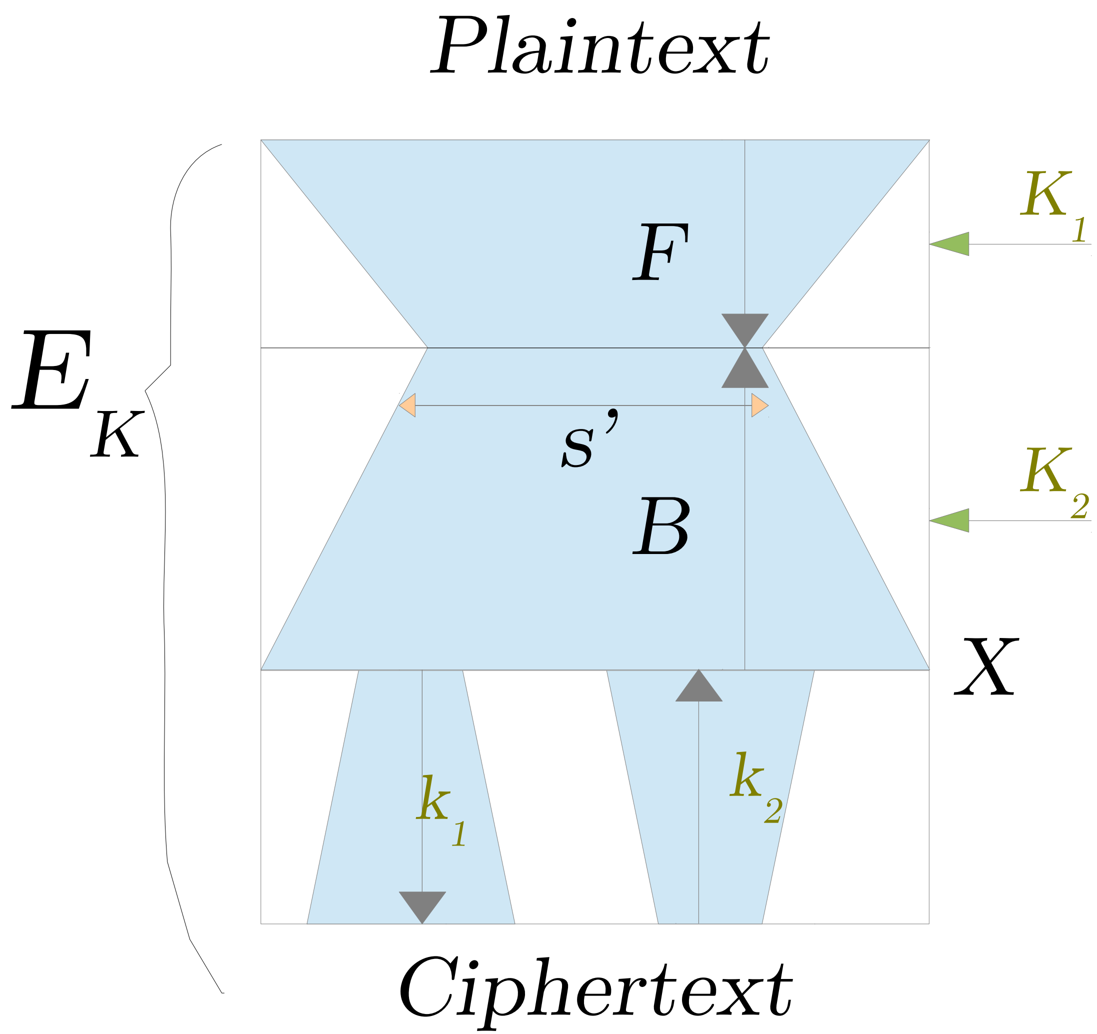
With Partial Matching [AS'08]



$K = K_1 \cup K_2$

$2^{|K_1|} + 2^{|K_2|} + 2^{|K|-s'}$

With Bicliques [KRS'11]



$K = K_1 \cup K_2$

$2^{|k_1|} + 2^{|k_2|} +$

$2^{|K_1|} + 2^{|K_2|} + 2^{|K|-s'}$

Bicliques

- Improvement of MITM attacks, but also...
- It can always be applied to reduce the total number of computations (at least the precomputed part) $\Rightarrow$ acceleration of exhaustive search [BKR'11] [2]
- Many other accelerated exhaustive search on LW block ciphers: PRESENT, LED, KLEIN, HIGHT, Piccolo, TWINE, LBlock ... (less than 2 bits of gain).
- Is everything broken? No.

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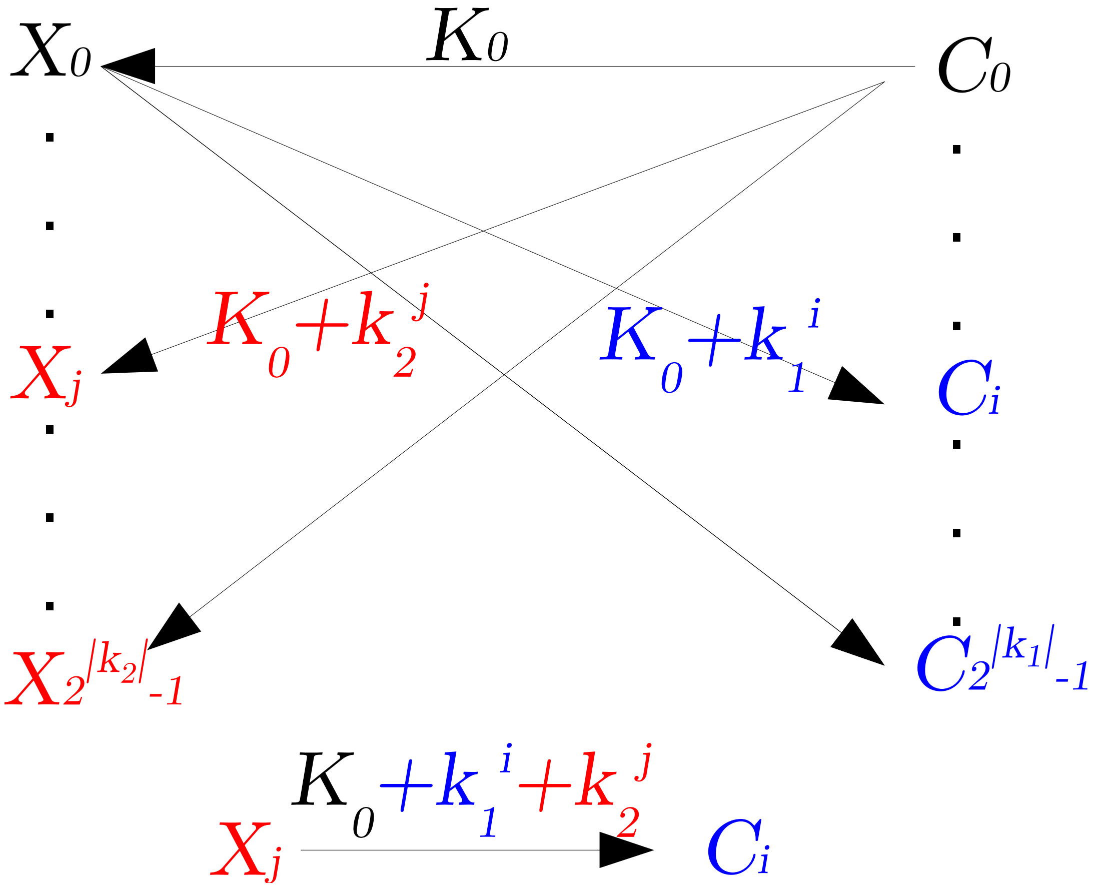
[2] Most important application: best key-recovery on AES-128 in $2^{126.1}$ instead of the naive 2^{128}.

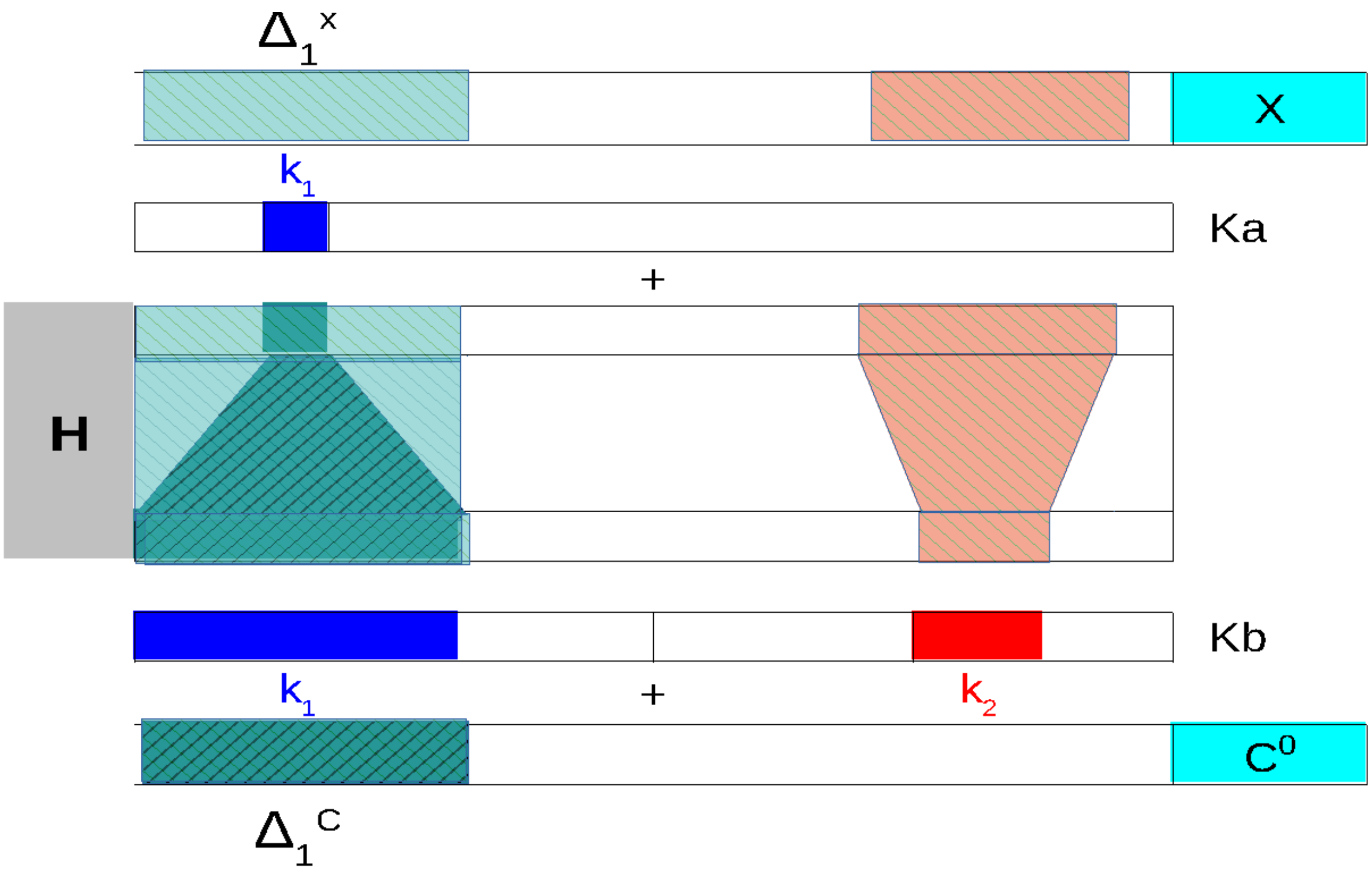
Bicliques



With
$2^{|k_1|}+2^{|k_2|}$
computations,
$2^{|k_1+k_2|}$
Transitions.

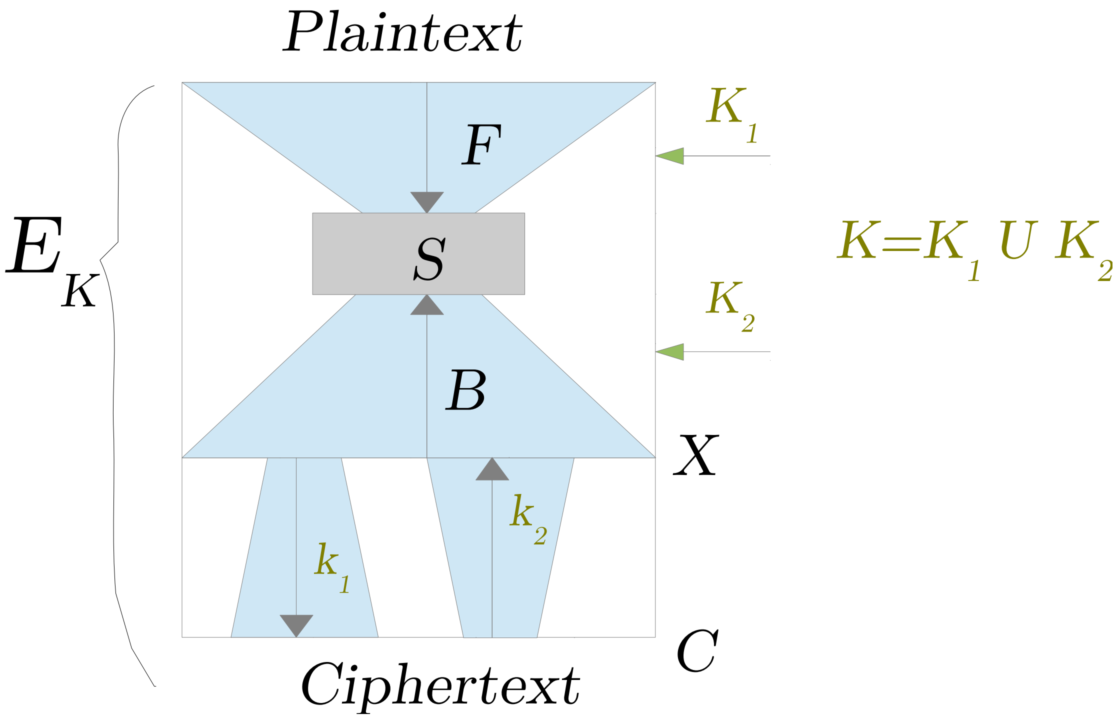
Improved Bicliques [CN-PV 13]

Can we build bicliques with only one pair of P-C?

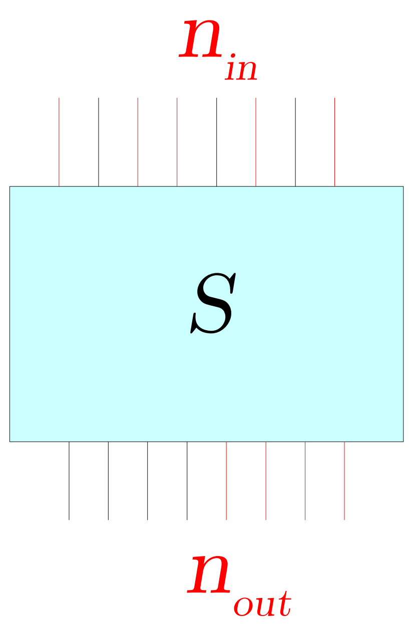


Sieve-in-the-Middle [CN-PV'13]

- Compute partial inputs and outputs of S
$\Rightarrow$ sieving with transitions instead of collisions.



When can we sieve?



- n_{in} known bits out of m: at most $2^{m-n_{in}}$ values for the n_{out} output bits.
- A transition exists with probability p.
- Sieve when $n_{in} + n_{out} > m \Rightarrow p < 1$

How do we sieve?

- We obtain a list L_A of partial inputs u and a list L_B of partial outputs v $\Rightarrow$ merge L_A and L_B with the condition (u, v) is a valid transition though S.

- Naive way costs $|L_A| \times |L_B| = 2^{|K_1|+|K_2|}$: no gain with respect to exhaustive search.

- We need an efficient procedure. Often S is a concatenation of S-boxes.

Merging the lists

Merging the lists with respect to R

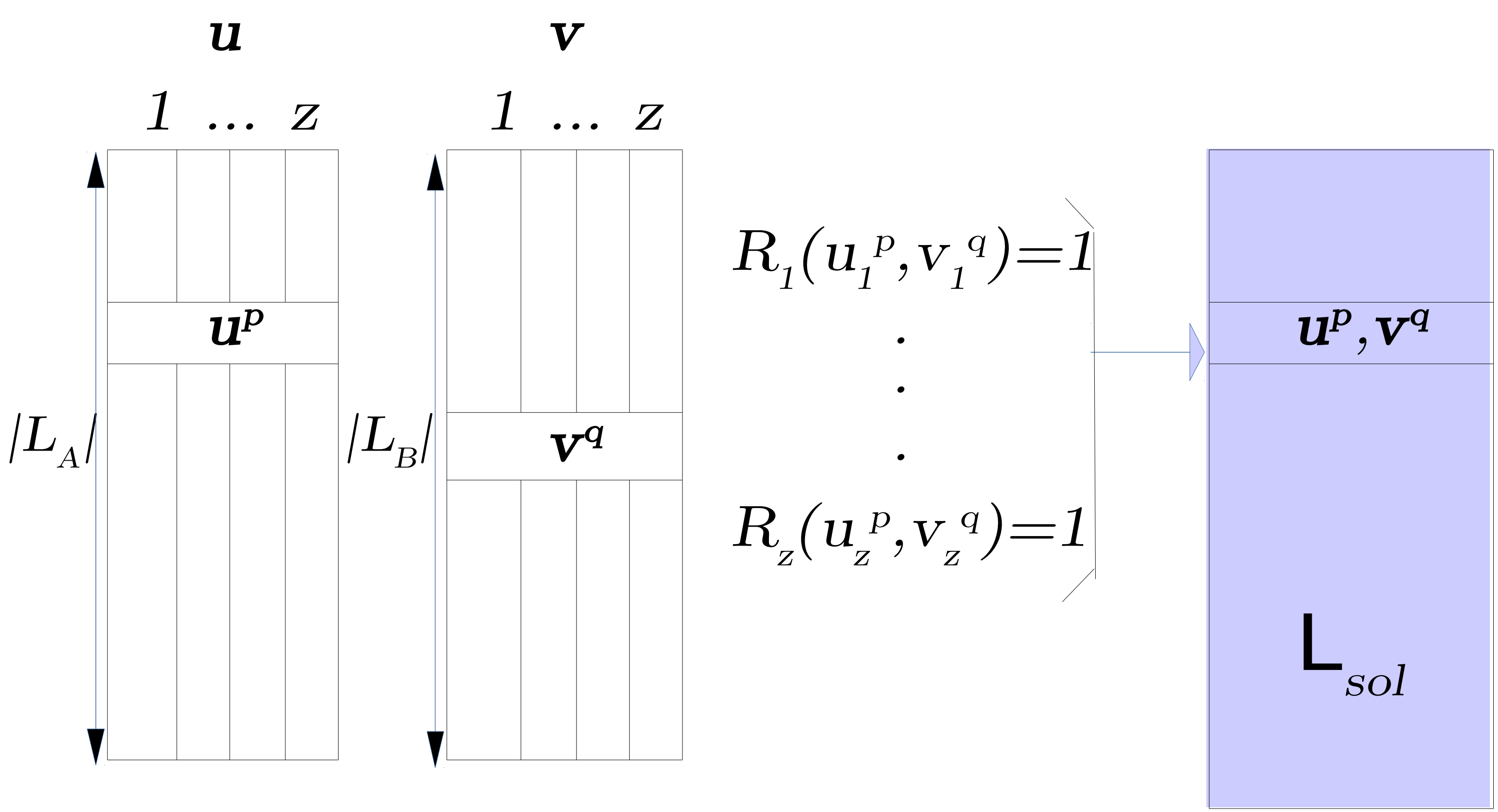
- R is group-wise, *i.e.* for z groups

$$R(u, v) = \Pi_{i=1}^{z} R_i(u_i, v_i)$$

  Find all $u \in L_A$ and $v \in L_B$ such that $R(u, v) = 1$.

- Subcase of the first problem in [N-P 11].
  First studied for rebound attacks.

Group-wise relation



Merging Algorithms

- Problem also appears in divide-and-conquer attacks (and rebound attacks).
- Solutions from list merging algorithms [N-P-11] and dissection algorithms [DDKS 12]
- Many applications: ARMADILLO2 [ABN-PVZ 11], ECHO256 [JN-PS 11], JH42 [N-PTV 11], Grøstl [JN-PP 12], Klein [LN-P 14], AES-like [JN-PP 14], Sprout [LN-P 15], Ketje [FN-PR 18]...

Some Applications SITM

- Reduced-round: PRESENT, DES, PRINCE, AES-biclique [Canteaut N-P Vayssieres 13]
- Reduced-round LBlock [Altawy Youssef 14]
- Best reduced-round KATAN [Fuhr Minaud 14]
- Reduced-round Simon [Song et al 14]
- Low-data AES [Bogdanov et.al 15]
  [Tao et al 15]
- MIBS80/PRESENT80 [Faghihi et al 16]

- Interesting for low data attacks...

Importance of Dedicated Cryptanalysis

Lightweight Dedicated Analysis

- Few cases broken by well known attacks (ex. Puffin or Puffin2 - multiple differentials)
- Happily, this is rare. Most of the times, new families or new ideas on known attacks exploiting the new properties are needed.
- Lightweight: more 'risky' design, lower security margin, simpler components.
- Often innovative constructions: dedicated attacks

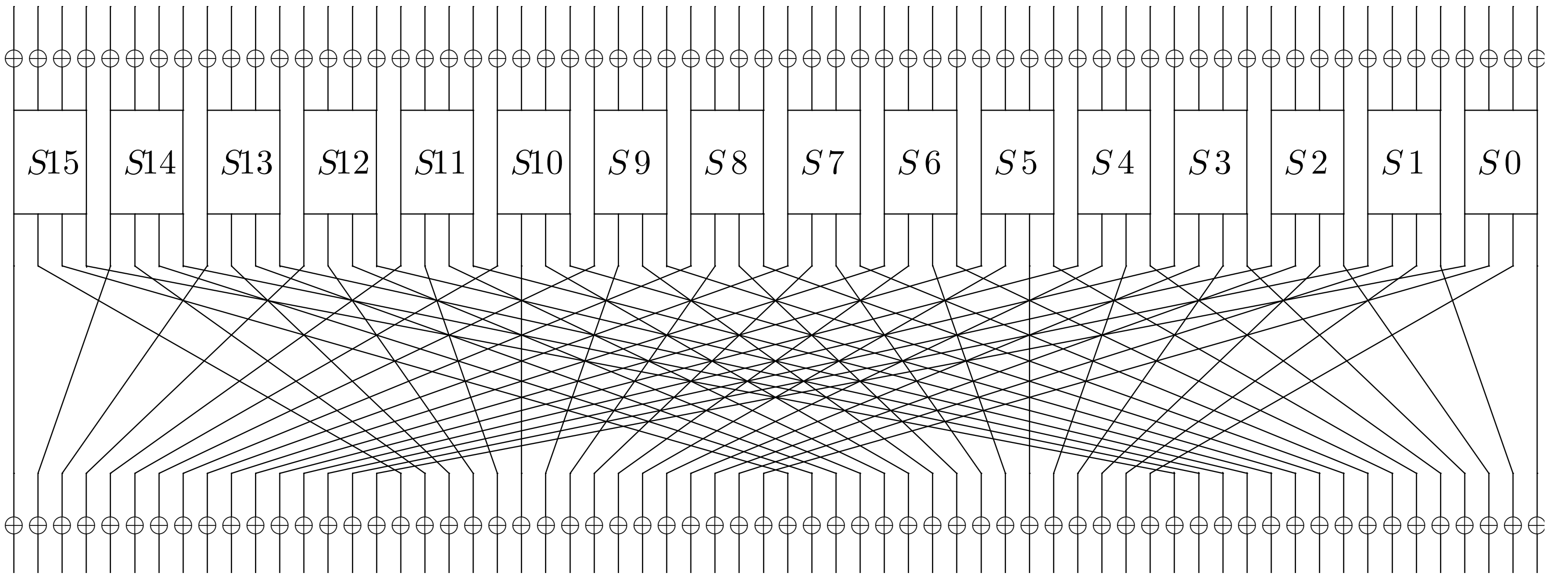
Ex: PRESENT and PRINTcipher

PRESENT [BKLPPRSV'07]

- One of the most popular ciphers, proposed in 2007, and now ISO/IEC standard.
- Very large number of analysis published (20+).
- Best attacks so far: multiple linear attacks (27r/31r).

PRESENT

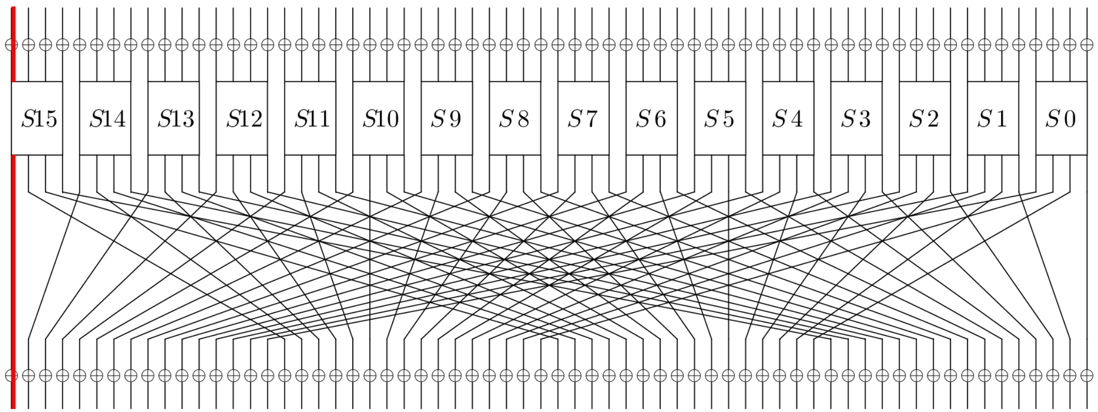
Block $n = 64$ bits, key 80 or 128 bits.



31 rounds + 1 key addition.

PRESENT

Linear cyptanalysis: because of the Sbox, a linear approximation 1 to 1 with bias 2^{-3} per round [O-09].

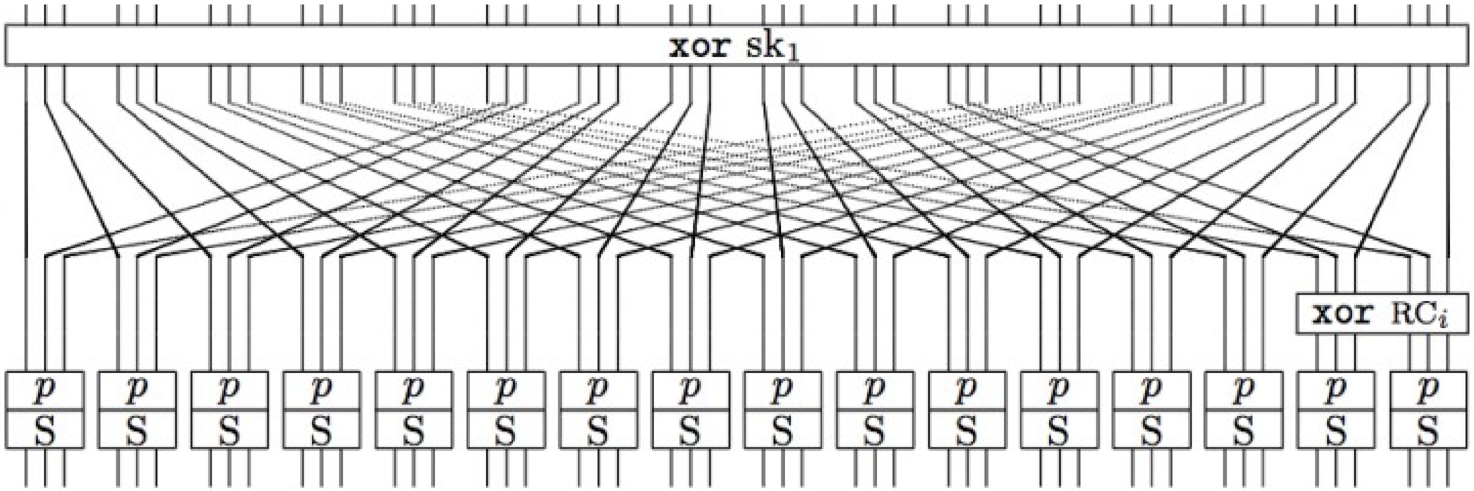


- Multiple linear attacks: consider several possible approxs simultaneously $\Rightarrow$ up to 27 rounds out of 31 [BN-14].

PRINTcipher

- Many PRESENT-like ciphers proposed, like Puffin, PRINTcipher
- Usually, weaker than the original.
- PRINTcipher[KLPR'10]: first cryptanalysis: invariant subspace attack[LAAZ'11].

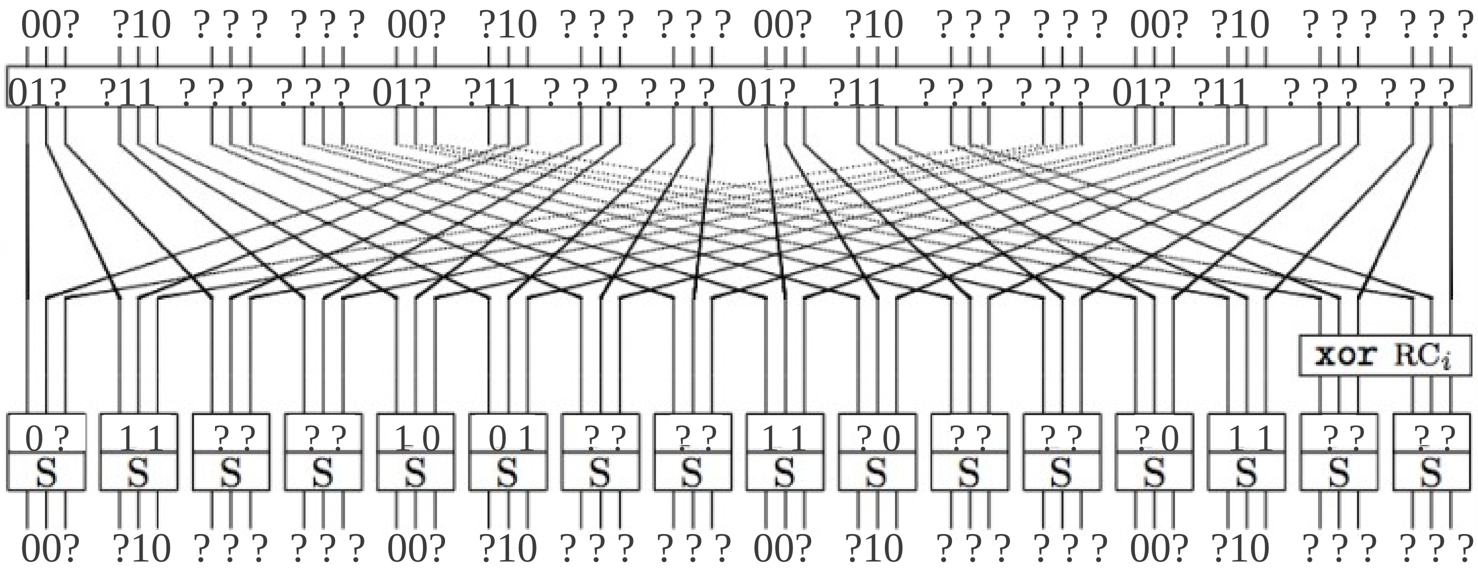
PRINTcipher



48 rounds.

The Invariant Subspace Attack [LAAZ'11]

With probability 1:



- Weak key attack, but a very bad property for 2^{51} keys...

The Invariant Subspace Attack

- More applications afterwards:
  iScream, Robin, Zorro, Midori.

- Importance of generalizing/understanding dedicated attacks:
  new families/techniques might appear.

Final remarks

Zorro - Hash Functions links

- Lightweight block cipher proposed [GGN-PS13] for easy masking.
- A modified AES with only four sboxes per round (SPN with partial non-linear layer).
- Bounds on number of active Sboxes? Computed using freedom degrees.
- Many analyses published. Problem: MC property $\Rightarrow$ devastating attack [BDDLT13, RASA13]

LED - Hash Functions links

- Lightweight block cipher proposed in [GPPR12].
- AES-like with simpler key-schedule and more rounds. Nice simple design.
- Analysis provided with respect to known key distinguishers (rebound-like). Seems like a lot of SHA-3 knowledge put into this design.

Hash functions links - Sum up

- Mitm, bicliques/initial structures:
  used for both scenarios
- Early abort $\leftarrow$ message modification techniques
- State-test tech. & choosing $\Delta_{in,out} \leftarrow$ Rebound attacks
- Mult. impos. diff. $\leftarrow$ mult. limited birthday distinguishers
- Using freedom degrees for bounds?... be careful!!
- Merging lists from rebounds/sieve in the middle
  $\rightarrow$ many applications
- *Other ex: AES distinguishers inspired on rebound attacks.*

Conclusion

To Sum Up

- Classical attacks, but also new dedicated ones exploiting the originality of the designs.
- Importance on generalizing: improvements, and dedicated might become well stablished techniques.
- Importance of reduced-round analysis to re-think security margin, or as first steps of further analysis.
- New ideas inspired by SHA-3: might help improving attacks further!
- Better identifying composite problems/ list merging situations might provide improved results.

To Sum Up[3]

A lot of ciphers to analyze/ a lot of work to do!

[3] Thank you to Christina Boura and Leo Perrin for their help with the figures and the slides.