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Multi-Stage Fault Attacks

Applications to the Block Cipher PRINCE

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Outline

1. Motivation
2. The PRINCE Block Cipher
3. A Multi-Stage Fault Attack on PRINCE

Cryptology

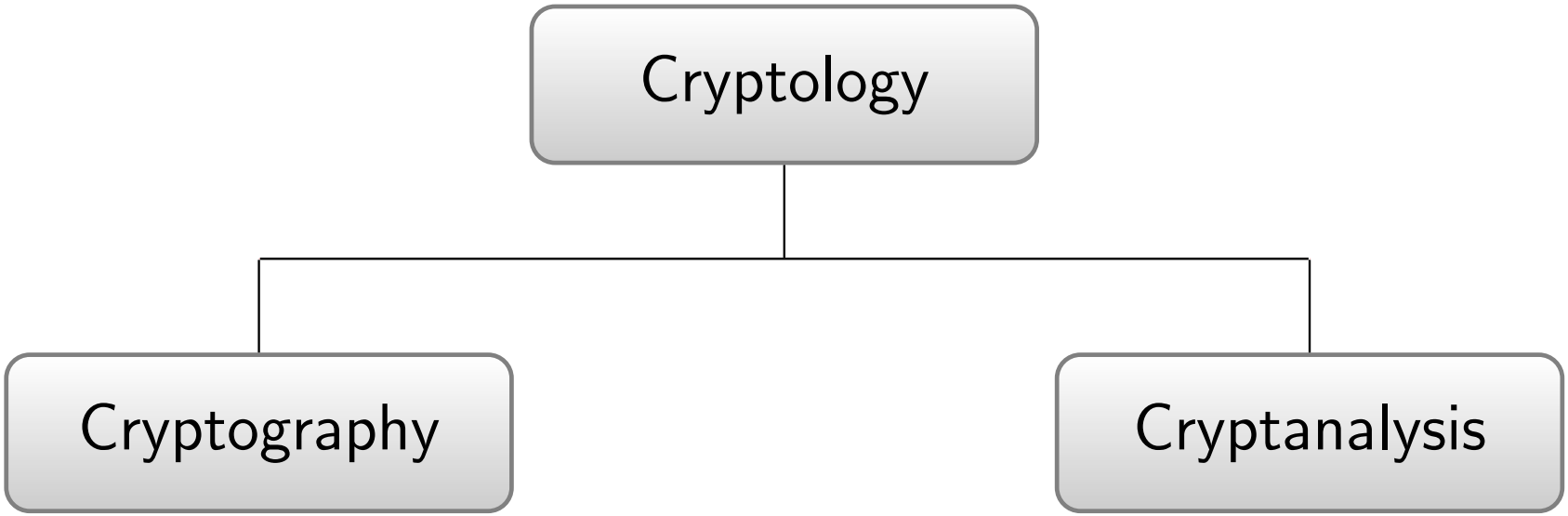

Figure: Overview on the field of cryptology.

Fields of Cryptanalysis

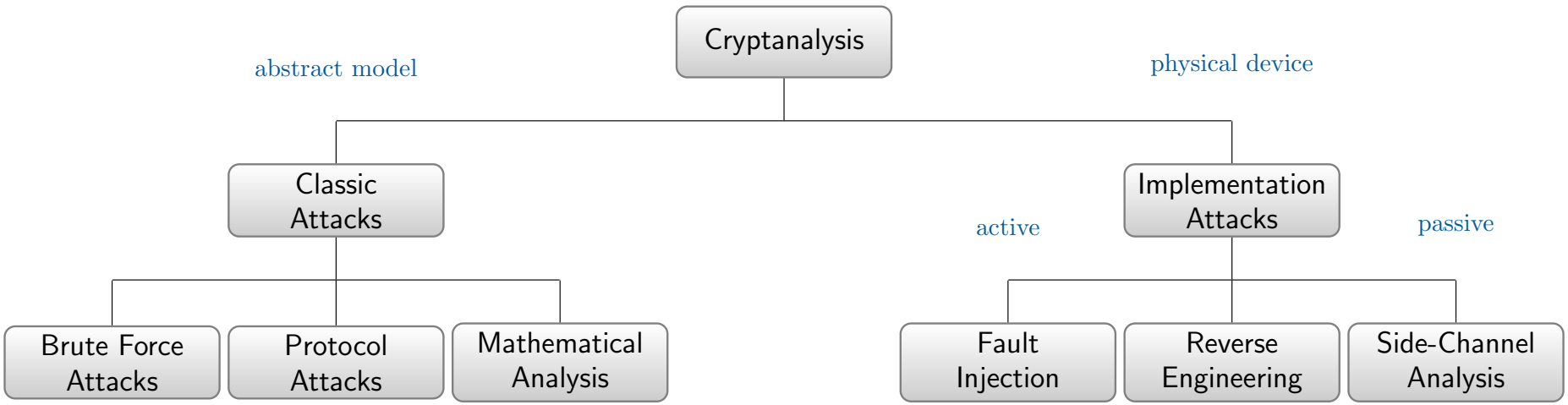

Figure: Overview on the different fields of cryptanalysis.

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At a Glance ...

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A CRYPTO NERD'S IMAGINATION:
HIS LAPTOP'S ENCRYPTED. LET'S BUILD A MILLION-DOLLAR CLUSTER TO CRACK IT.
NO GOOD! IT'S 4096-BIT RSA!
BLAST! OUR EVIL PLAN IS FOILED!

At a Glance ...

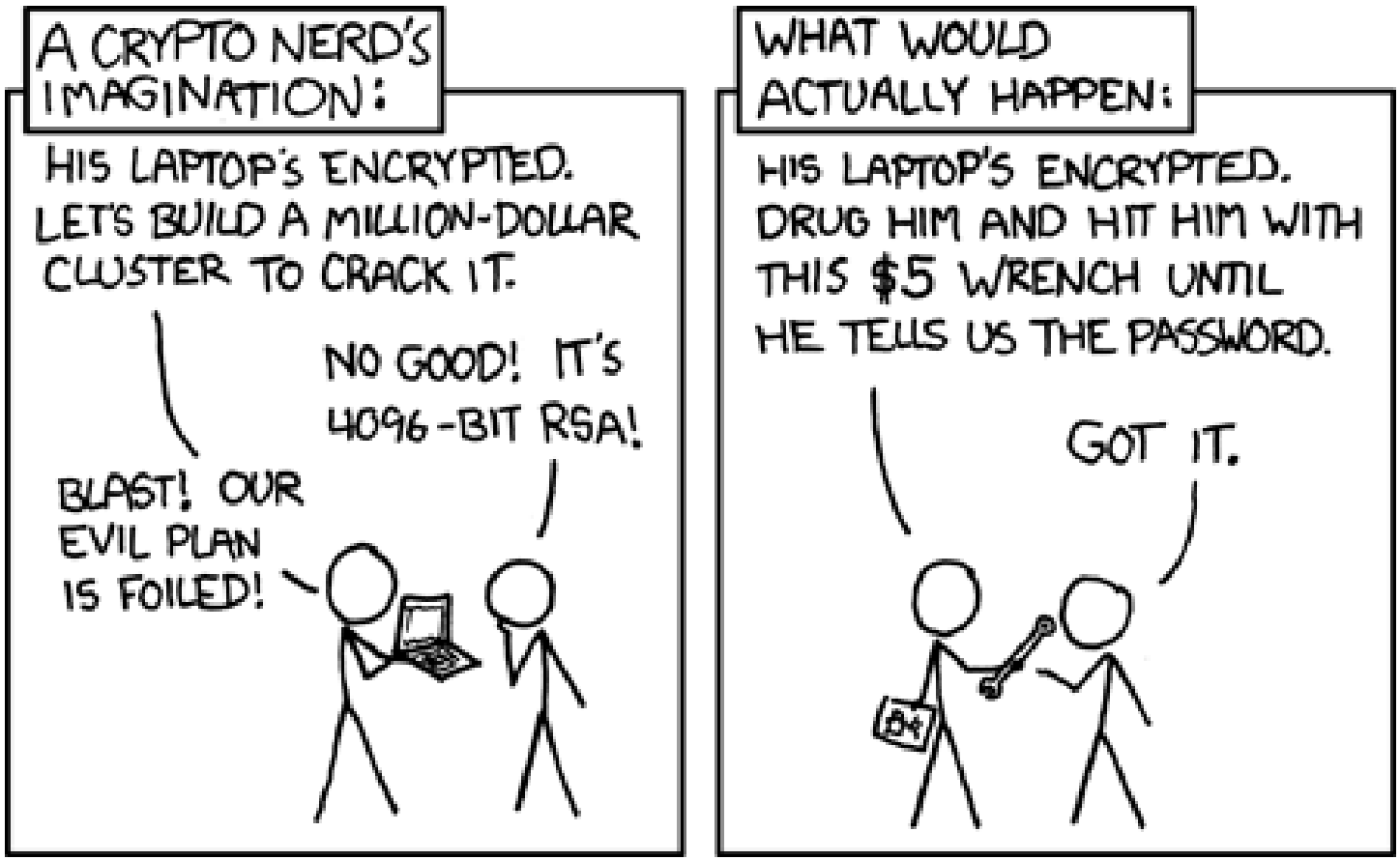
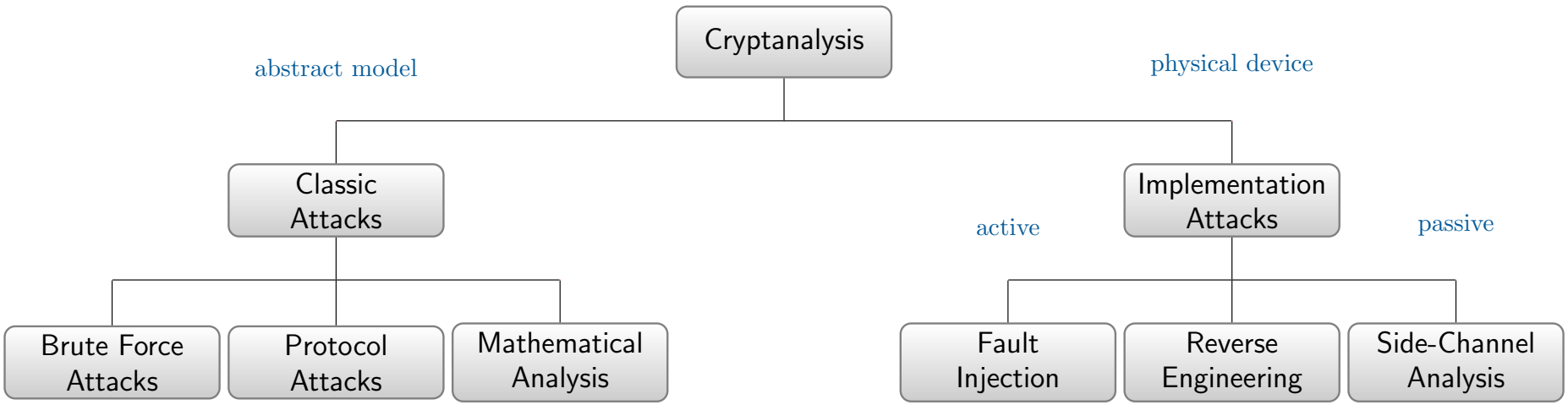


Figure: http://xkcd.com/538

Fields of Cryptanalysis



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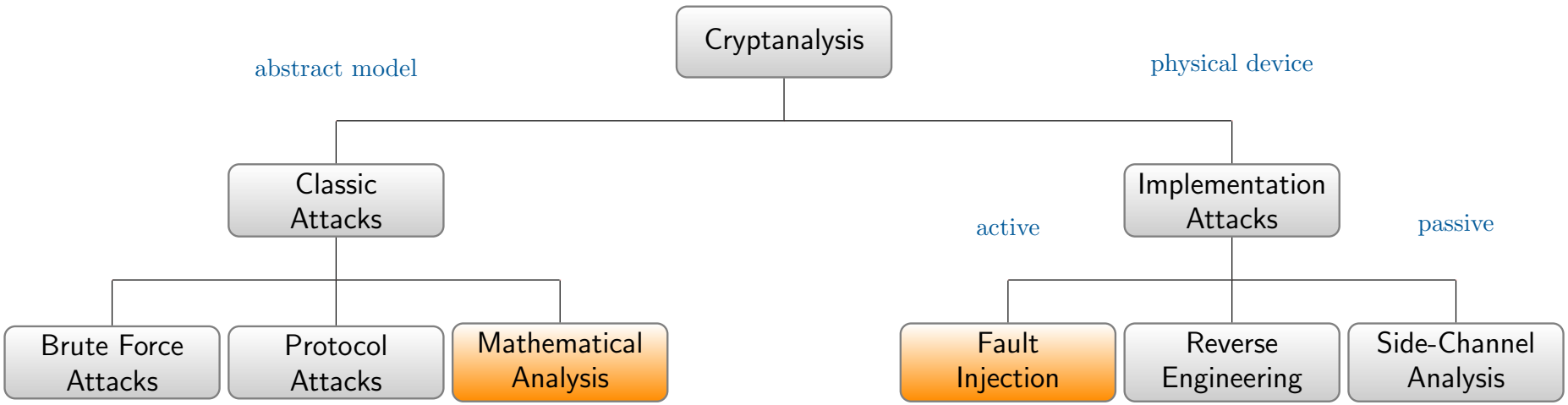

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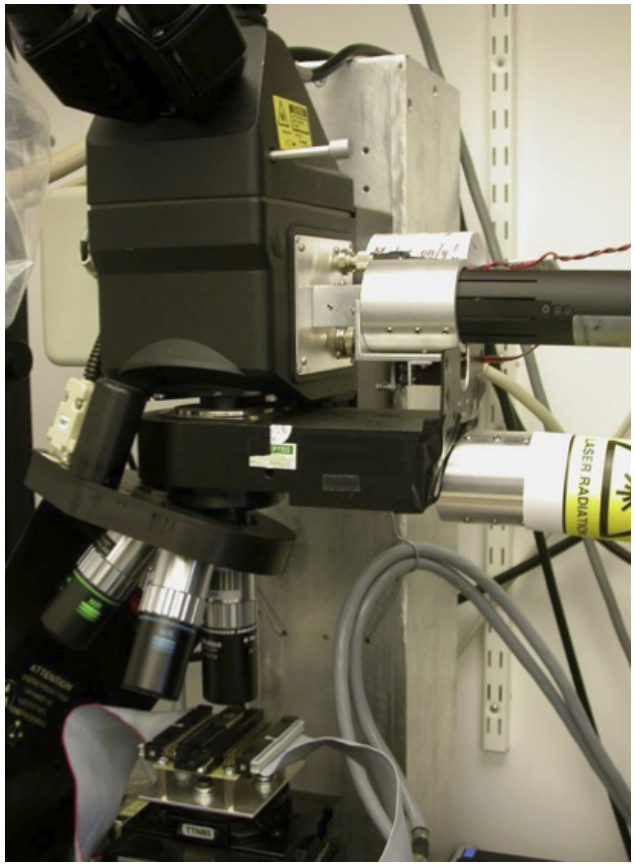
Fault Attacks

Characteristics

- First appearances in 1998* and 2001†.
- By injecting faults into the electronical circuit, the attacker tries to extract secret informations from the latter (e.g. a key).
- Lead to powerful new attack techniques and chip manufacturers were forced to rethink their designs.



* E. Biham and A. Shamir, Differential Fault Analysis of Secret Key Cryptosystems, In: Burton S. Kaliski Jr. (ed.) *CRYPTO* 1997, LNCS, vol. **1294**, Springer Heidelberg 1997, pp. 513–525.

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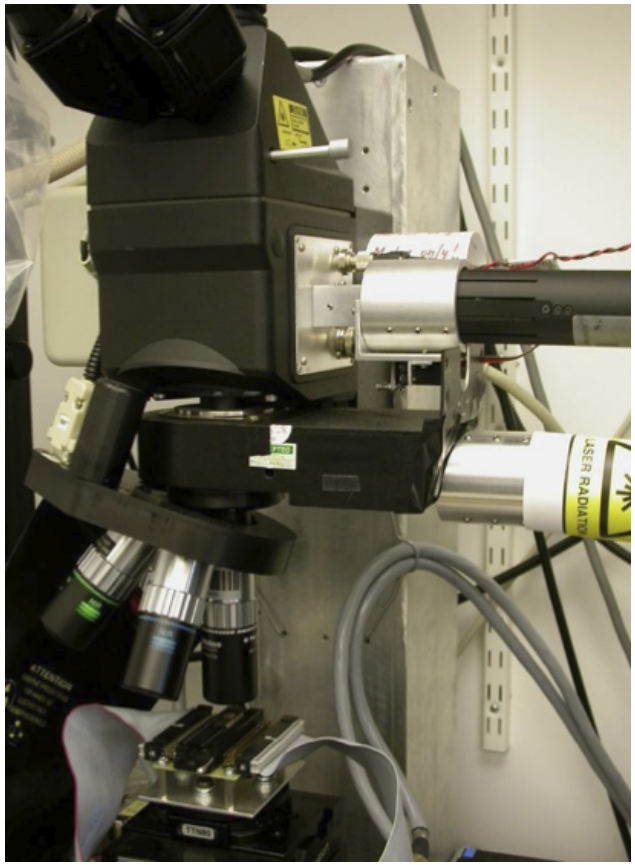

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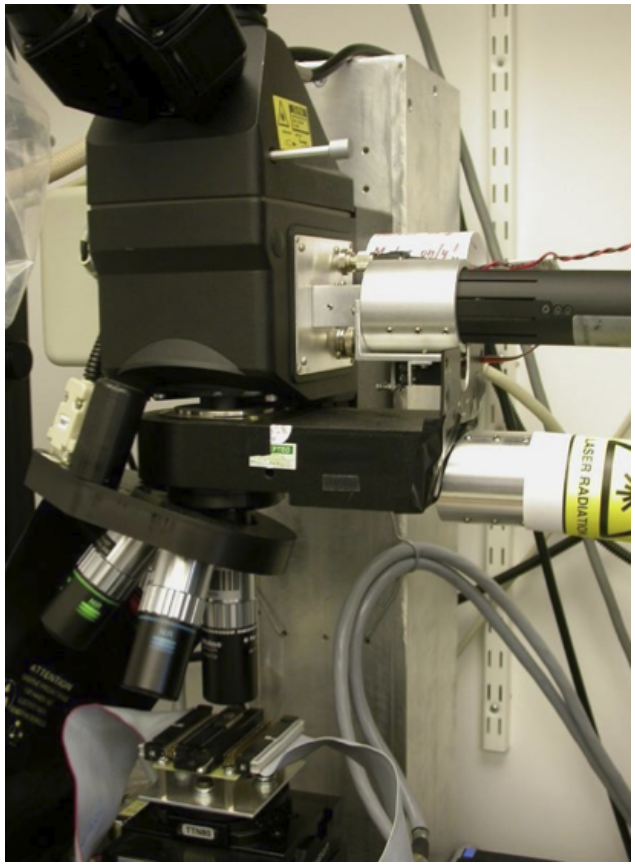

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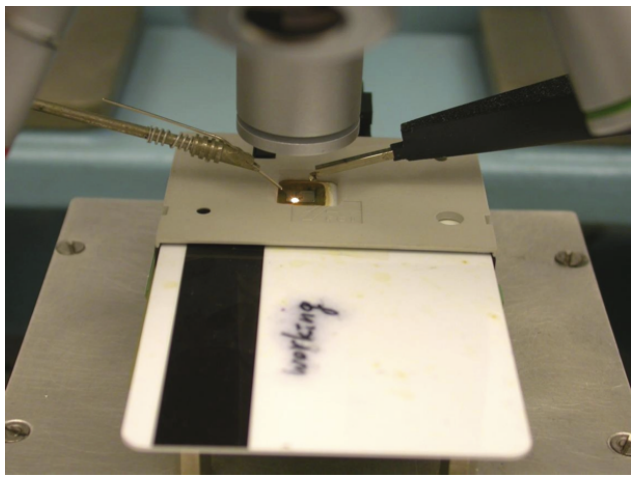
Techniques to Induce Faults

- Manipulation of the power-supply voltage to cause miscalculations.
- Manipulation of the circuit's clock.
- Parasitic charge-carrier generation by a laser beam.



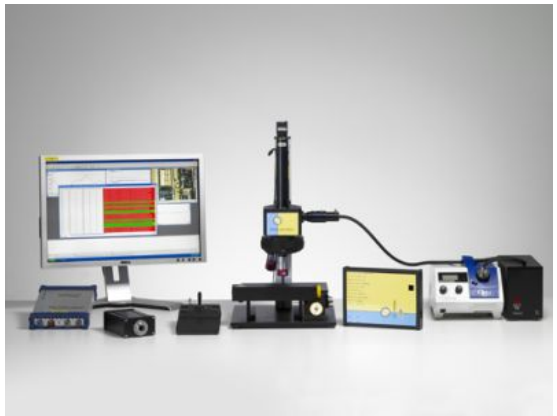


Figure: www.riscure.com

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Some Attacks using Fault Injections

- C. Aumueller et al. Fault Attacks on RSA With CRT: Concrete Results and Practical Countermeasures, *CHES* 2002.
- M. Mohamed, S. Bulygin and J. Buchmann, Improved Differential Fault Analysis of Trivium, *COSADE* 2011.
- M.S. Pedro, M. Soos and S. Guilley, FIRE: Fault Injection for Reverse Engineering, In: C.A. Ardagana and J. Zhou (eds.) *Security and Privacy of Mobile Devices in Wireless Communication* 2011.

Overview

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1. Motivation

2. The PRINCE Block Cipher

3. A Multi-Stage Fault Attack on PRINCE

Definition

Given a block size of n_1 bits and a key size of n_2 bits a block cipher is specified by an encryption function

$$E : \{0,1\}^{n_1} \times \{0,1\}^{n_2} \to \{0,1\}^{n_1}, (m,k) \mapsto c$$

and a decryption function

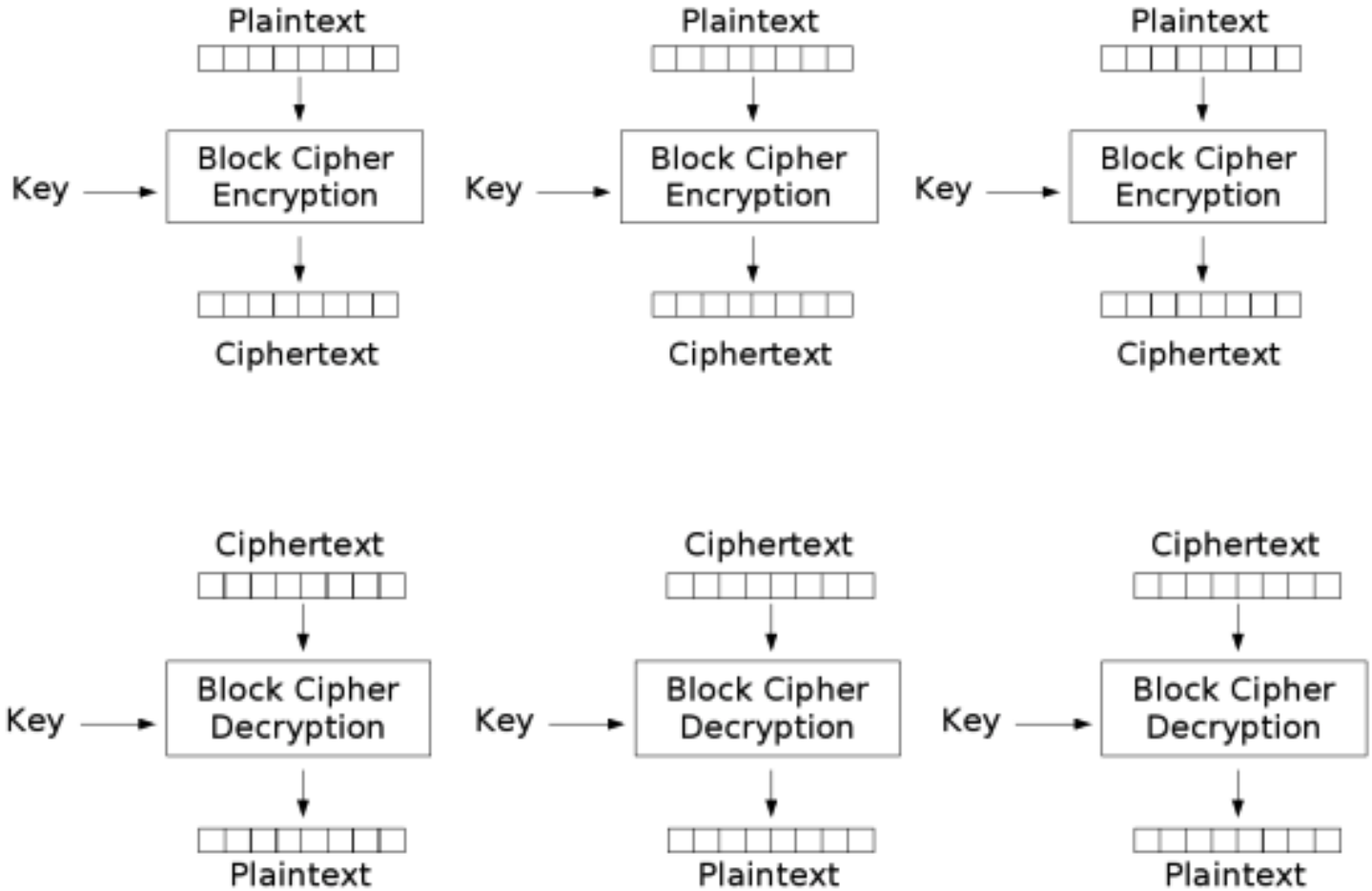
$$D : \{0,1\}^{n_1} \times \{0,1\}^{n_2} \to \{0,1\}^{n_1}, (c,k) \mapsto m$$

such that

$$D_k(E_k(m)) = m$$

for all plaintext messages $m \in \{0,1\}^{n_1}$ and all keys $k \in \{0,1\}^{n_2}$.

Overview on Block Ciphers



General Features

- Uses a 64-bit state and a 128-bit key.
- Based on the so-called *FX* construction.
- Core of the cipher is based on a Substitution-Permutation Network (SPN) and has 10 encryption rounds divided by a middle layer.
- Furthermore the core of PRINCE features the so-called α-reflection property. Due to this it holds that:

$$D_{(k_0 \| k_0' \| k_1)}(\cdot) = E_{(k_0' \| k_0 \| k_1 \oplus \alpha)}(\cdot)$$

  where $\alpha = \texttt{c0ac29b7c97c50dd}$.
- This keeps the hardware costs low and produces only small overheads. (Applications: smart cards, sensor networks, "internet-of-things" etc.)

* J. Borghoff et al., PRINCE – A Low-Latency Block Cipher for Pervasive Computing Applications, In: K. Sako and X. Wang (eds.) *ASIACRYPT* 2012, LNCS, vol. **7658**, Springer Heidelberg 2012, pp. 208–225.

The 128-bit key k is split into two parts k_0 and k_1 of 64 bit each,

$$k = k_0 \parallel k_1$$

and extended to 192 bits by the following mapping:

$$(k_0 \parallel k_1) \mapsto (k_0 \parallel k_0' \parallel k_1) := (k_0 \parallel (k_0 >>> 1) \oplus (k_0 >> 63) \parallel k_1)$$

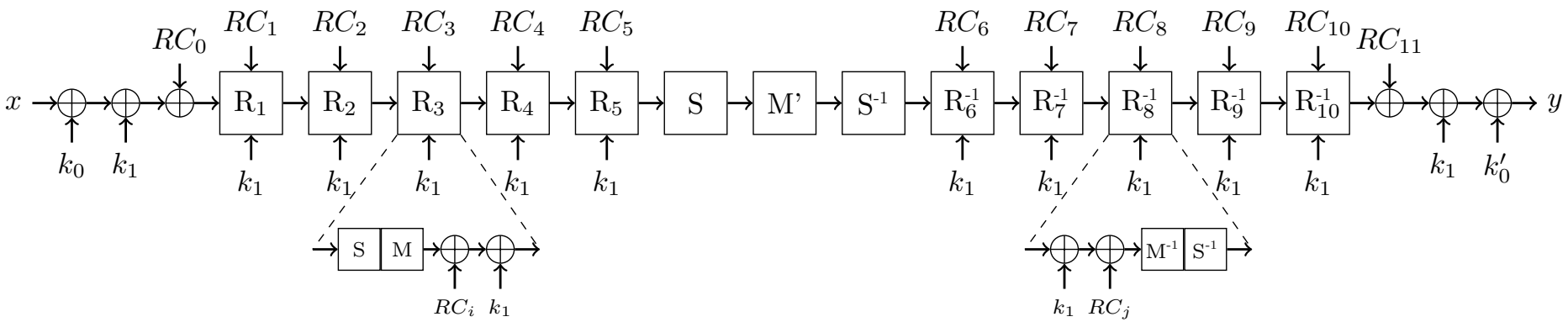
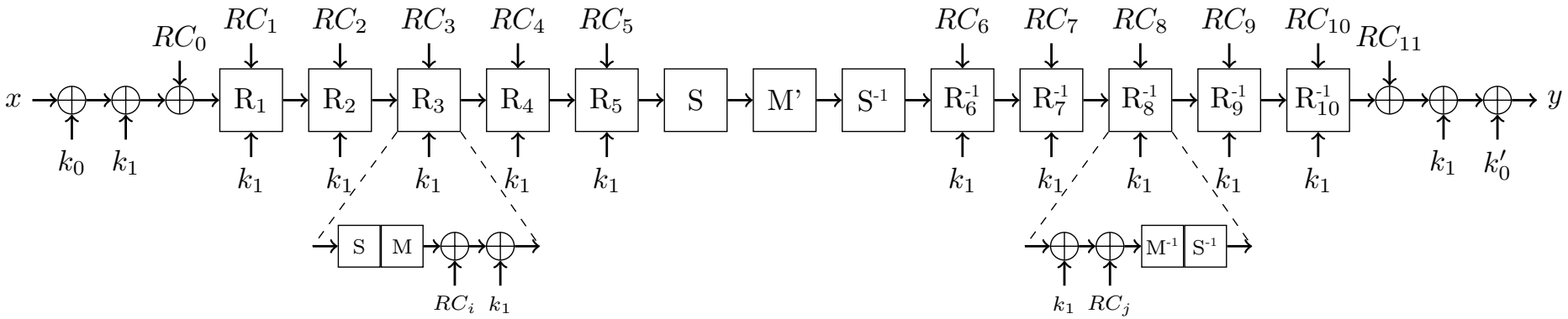


Figure: Layout of PRINCE.

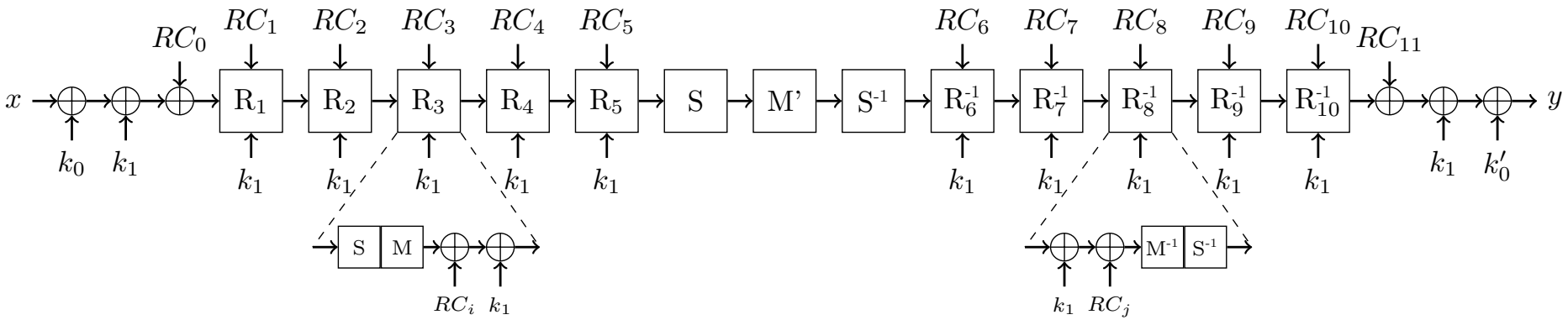
Components of PRINCE



- k_i-add: The 64-bit subkey k_i is XORed to the state.
- S-Layer: All state nibbles are substituted using the 4-bit SBox below.

x	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
$S[x]$	B	F	3	2	A	C	9	1	6	7	8	0	E	5	D	4

Components of PRINCE



- M / M'-Layer: The 64-bit state is multiplied with a 64 $\times$ 64 matrix M resp. M', where $M = SR \circ M'$ and SR shifts row i of the state matrix cyclically to the left by $i - 1$ nibbles.
- RC_i-add: A 64-bit round constant is XORed to the state.

i	RC_i
0 – 2	0000000000000000, 13198a2e03707344, a4093822299f31d0
3 – 5	082efa98ec4e6c89, 452821e638d01377, be5466cf34e90c6c
6 – 8	7ef84f78fd955cb1, 85840851f1ac43aa, c882d32f25323c54
9 – 11	64a51195e0e3610d, d3b5a399ca0c2399, c0ac29b7c97c50dd

Overview

1. Motivation

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What's a Multi-Stage Fault Attack?

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Outline

- Obtain one (or more) pair(s) of correct and faulty ciphertexts c and c'.
- Use *Differential Fault Analysis* to examine the ciphertext pairs (c, c') and obtain informations about the secret key k.
- Repeat the above scheme if the attacked block cipher uses multiple independent subkeys, i.e. if $k = k_0 \parallel \cdots \parallel k_n$ and the k_i are not "connected" through a key schedule.

Recall: PRINCE uses two independent subkeys.

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More Questions

- How good does a fault injection need to be controllable by an attacker such that informations about the secret key can be derived?
- In other words: Can we use ciphertexts obtained from arbitrary faults or are there any requirements in order to produce “useful” faulty ciphertexts?
- What exactly is *Differential Fault Analysis* and how does it work in the case of PRINCE?

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Requirements

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Capabilities of an Attacker

- Known Plaintext Attack: We assume that the attacker is able to generate an arbitrary number of plaintext, (faulty) ciphertext triples (m, c, c').
- Kerckhoffs Principle or "The enemy knows the system": The design of the cipher is known to the adversary. (No security by obscurity)

Fault Models

- Temporal Resolution: Fault injection timing is controllable very precisely, i.e. injection after a specific operation of the cipher.
- Spatial Resolution: Injection effects a single nibble (4-bit value) of the whole state. The affected nibble itself is either **known** (model: RKF) or **unknown** (model: RUF).
- Effects: Injection changes the state nibble to a random and unknown 4-bit value.

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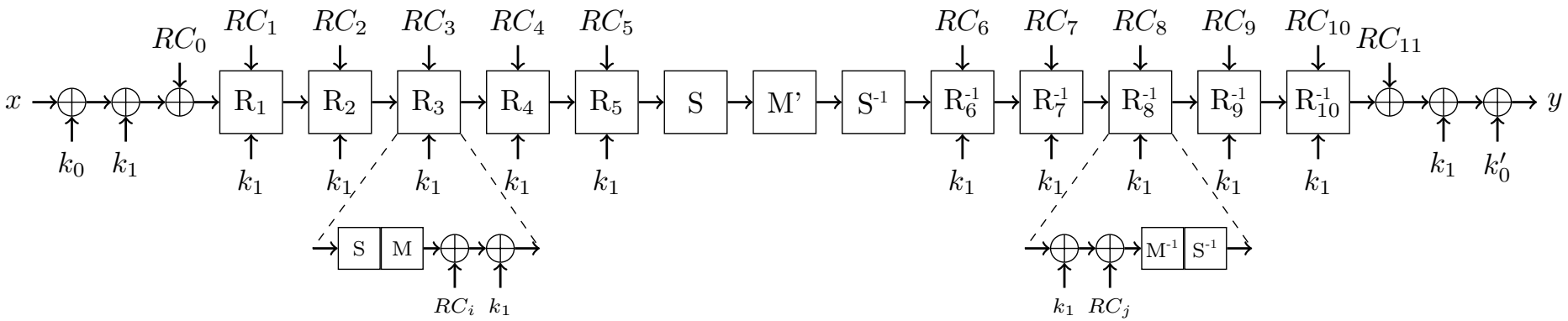
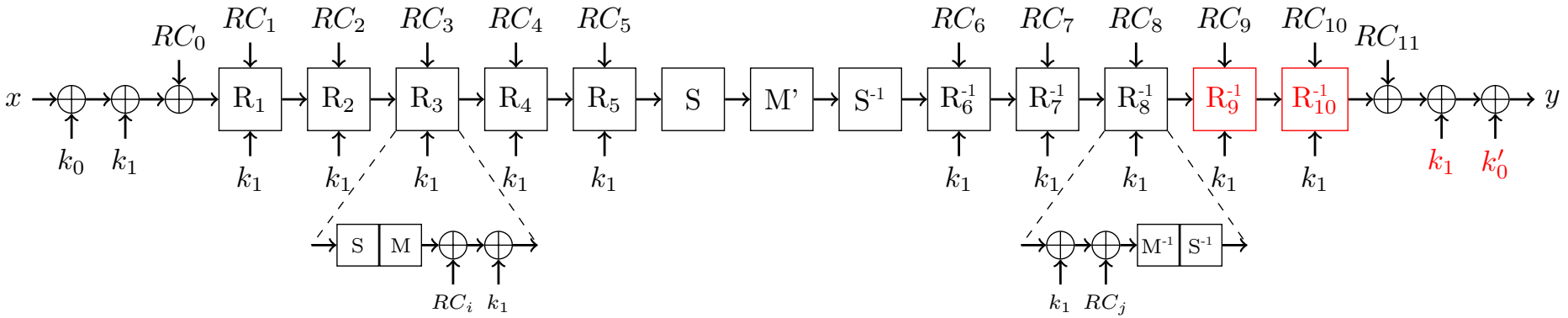
Where to Inject Faults?

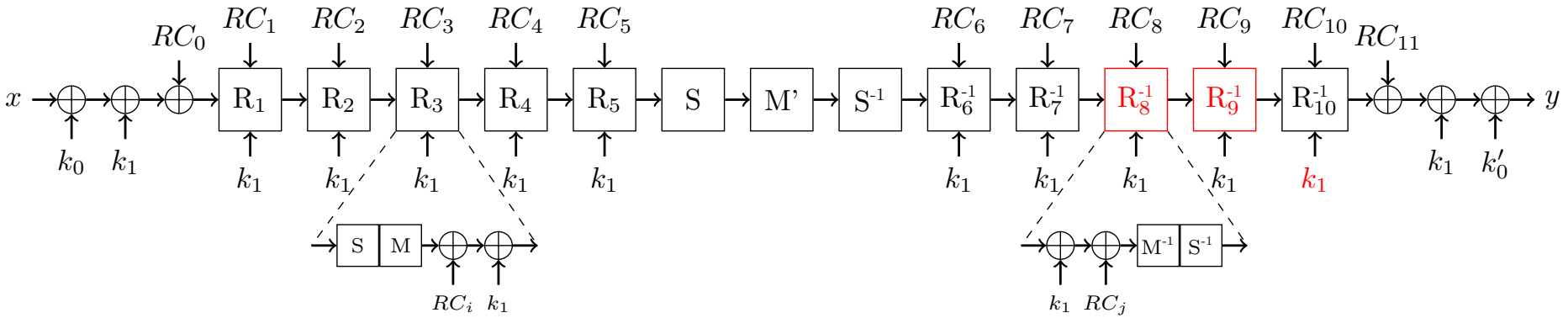


Attack Stage 0



- Inject fault in R_9^{-1}.
- Analyse fault propagation and ciphertext pairs.
- Obtain informations on $k_0' \oplus k_1$.

Attack Stage 1



- Inject fault in R_8^{-1}.
- Analyse fault propagation and ciphertext pairs.
- Obtain informations on k_1.

Definition

Let $a = b_0 \parallel b_1 \parallel b_2 \parallel b_3$ be a 4-bit value and let $j \in \{0, \ldots, 3\}$. Then we define the map:

$$\varphi : \mathbb{B}^4 \times \{0, \ldots, 3\} \longrightarrow \mathbb{B}^4, (a, j) \longmapsto \varphi_j(a)$$

where $\varphi_j(a)$ is equal to a but with the j-th bit b_j set to 0.

Bit Pattern

j	$\varphi_j(a)$			
0	0	b_1	b_2	b_3
1	b_0	0	b_2	b_3
2	b_0	b_1	0	b_3
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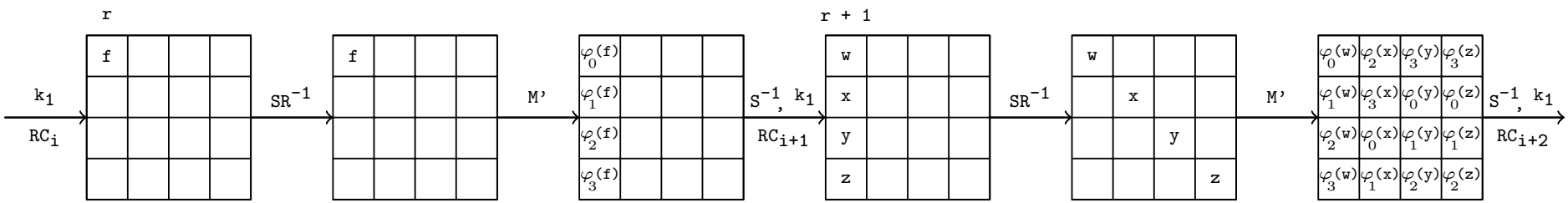
Fault Propagation over 2 Rounds



Fault Equations

Let v_i, v_i', k_i and q_i be variables. We substitute the nibbles of correct and faulty ciphertexts (intermediate states) for v_i and v_i', key nibbles for k_i and round constant nibbles for q_i.

$$E_i : SBox(v_i \oplus k_i \oplus q_i) \oplus SBox(v_i' \oplus k_i \oplus q_i) = \begin{cases} \varphi_{j_i}(w), & i \in \{0, \ldots, 3\} \\ \varphi_{j_i}(x), & i \in \{4, \ldots, 7\} \\ \varphi_{j_i}(y), & i \in \{8, \ldots, 11\} \\ \varphi_{j_i}(z), & i \in \{12, \ldots, 15\} \end{cases}$$

$$(j_i)_{i=0,\ldots,15} = \begin{cases} (0,1,2,3,2,3,0,1,3,0,1,2,3,0,1,2), & l \in \{0,7,10,13\} \\ (3,0,1,2,1,2,3,0,2,3,0,1,2,3,0,1), & l \in \{1,4,11,14\} \\ (2,3,0,1,0,1,2,3,1,2,3,0,1,2,3,0), & l \in \{2,5,8,15\} \\ (1,2,3,0,3,0,1,2,0,1,2,3,0,1,2,3), & l \in \{3,6,8,12\} \end{cases}$$

Definition

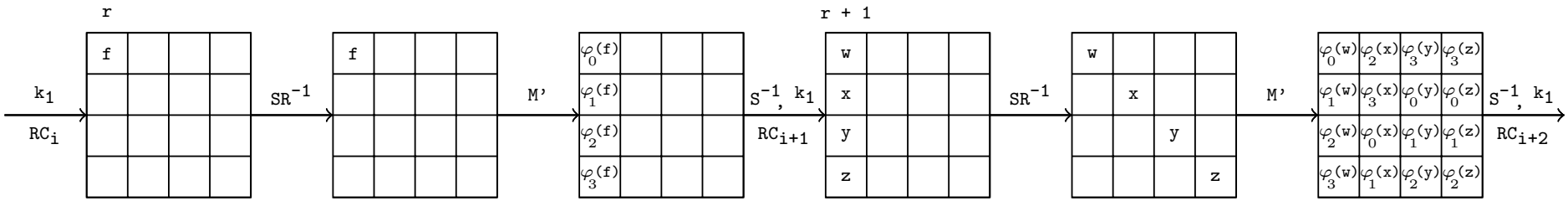
For every fault eqaution E_i we introduce a *key nibble candidate set* S_i with

$$S_i = \{(t, u) \mid t, u \in \mathbb{B}^4\}$$

for $i \in \{0, \ldots, 15\}$. Furthermore let $S = (S_i)_{i=0,\ldots,15}$.

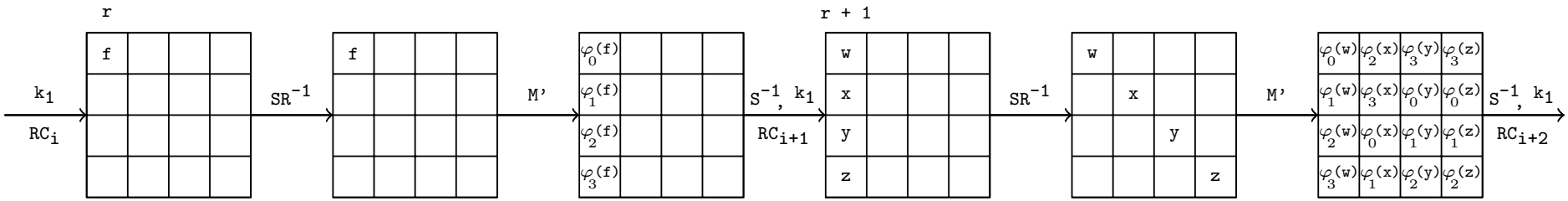
DFA Algorithm:

Input: (c, c') (intermediate state (v, v') for the 2nd stage)
Output: Set S containing candidates for $k_0' \oplus k_1$ (or k_1 for the 2nd stage)
return `outer_filtering(inner_filtering(evaluation(`c, c'`)))`



Overview on the Single Steps

- `evaluation`: Compute $E_i(u) = t$ for all $u \in \mathbb{B}^4$ and save the result (u, t) to the set S_i.
- `inner_filtering`: Discard all tuples (u, t) from S_i where t doesn't match the pattern φ_{j_i} associated with E_i.
- `outer_filtering`: Exploit the fact that the elements of the sets $S_{4 \cdot m}, \ldots, S_{4 \cdot m+3}$ are derived from a commen preimage to discard even more invalid tuples (u, t).



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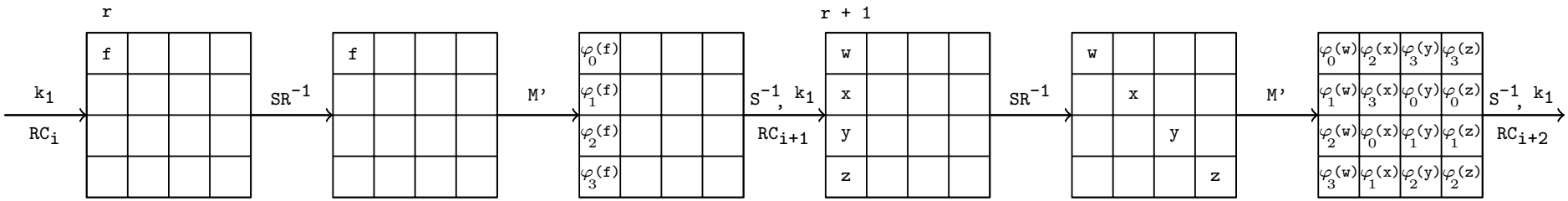

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Example

Assume we have the following setup:

$$k = \texttt{01234567 89ABCDEF 01234567 89ABCDEF}$$
$$m = \texttt{01234567 89ABCDEF}$$
$$c = \texttt{0A72342A 02193229}$$
$$c' = \texttt{21A19DCD 25D7433C}$$

The faulty ciphertext c' was obtained by injecting the error value $e = \texttt{0xC}$ into nibble s_0 of the state at the beginning of round R_9^{-1}.

A Fault Attack on PRINCE

As a reminder we list again the possible index pattern below.

j	$\varphi_j(a)$			
0	0	b_1	b_2	b_3
1	b_0	0	b_2	b_3
2	b_0	b_1	0	b_3
3	b_0	b_1	b_2	0

Table: Distribution of key nibbles after `evaluation` (1st column) ...

S_i	$\sum$	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
$\#S_0$	16	2	0	4	0	0	0	2	2	0	0	0	0	4	2	0
$\#S_1$	16	2	0	0	4	0	0	2	0	0	0	2	2	0	2	2
$\#S_2$	16	2	0	0	0	0	0	2	0	4	2	0	0	2	2	2
$\#S_3$	16	0	0	0	0	2	2	0	2	2	2	2	2	0	0	2

Apply the same technique to the other sets $S_4, \ldots, S_{15}$. As a result there remain only $2^{20} = 1.048.576$ from the initial 2^{64} candidates for $k_0' \oplus k_1$.

A Fault Attack on PRINCE

As a reminder we list again the possible index pattern below.

j	$\varphi_j(a)$			
0	0	b_1	b_2	b_3
1	b_0	0	b_2	b_3
2	b_0	b_1	0	b_3
3	b_0	b_1	b_2	0

Table: ... after `inner_filtering` ...

S_i	$\sum$	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
$\#S_0$	8	2	0	4	0	0	0	2	0	0	0	0	0	0	0	0
$\#S_1$	4	2	0	0	0	0	0	0	0	0	0	2	0	0	0	0
$\#S_2$	8	2	0	0	0	0	0	0	0	4	0	0	0	2	0	0
$\#S_3$	8	0	0	0	0	0	2	0	2	0	2	0	2	0	0	0

Apply the same technique to the other sets $S_4, \ldots, S_{15}$. As a result there remain only $2^{20} = 1.048.576$ from the initial 2^{64} candidates for $k_0' \oplus k_1$.

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Table: ... and after `outer_filtering`.

S_i	$\sum$	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
$\#S_0$	4	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0
$\#S_1$	2	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0
$\#S_2$	4	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0
$\#S_3$	2	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0

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A Fault Attack on PRINCE

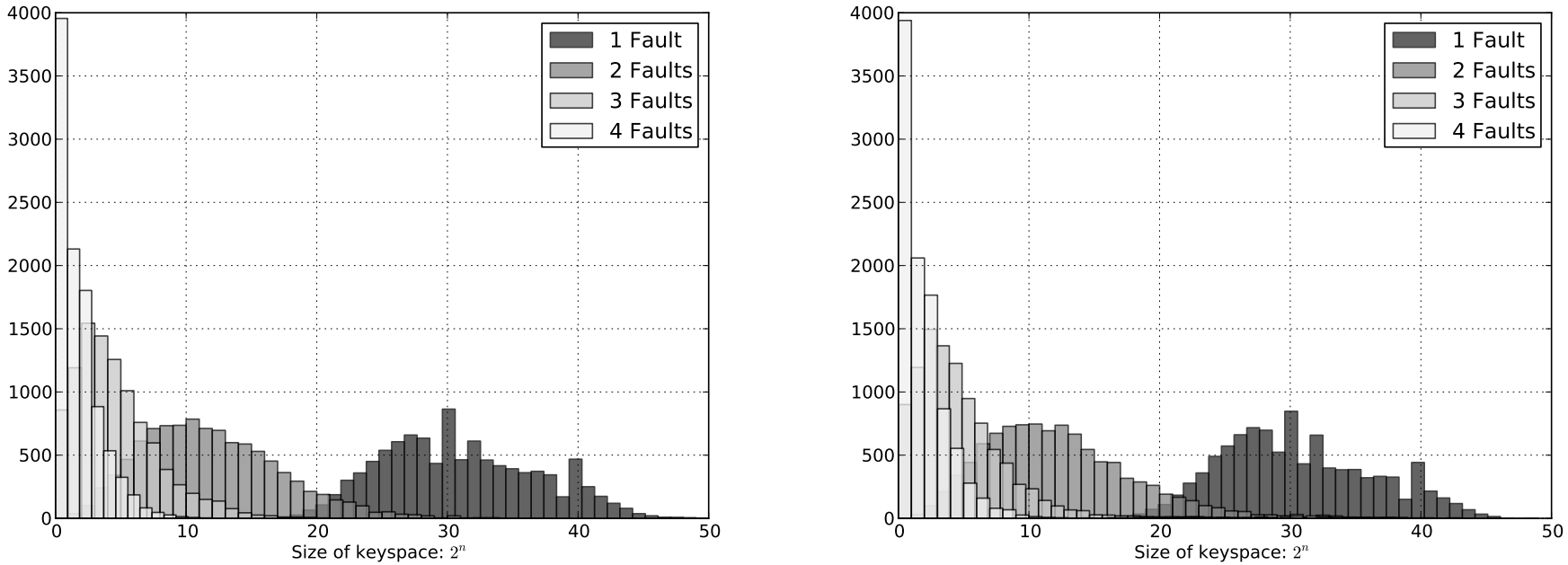

Figure: Experimental results for stage 0 (left) and stage 1 (right). The data was obtained through 10.000 runs of the attack using fault model RUF.

A Fault Attack on PRINCE

Table: Statistics for $k_0' \oplus k_1$ and k_1 candidates after stage 0 and 1.

	stage 0				stage 1			
# keys / # faults	1	2	3	4	1	2	3	4
min	$2^{17.00}$	1	1	1	$2^{16.00}$	1	1	1
max	$2^{50.00}$	$2^{38.00}$	$2^{24.00}$	$2^{12.00}$	$2^{49.00}$	$2^{44.00}$	$2^{40.00}$	$2^{43.00}$
avg	$2^{30.89}$	$2^{11.44}$	$2^{4.12}$	$2^{1.47}$	$2^{30.41}$	$2^{11.64}$	$2^{4.44}$	$2^{1.82}$
median	$2^{34.50}$	$2^{19.50}$	$2^{12.50}$	$2^{7.00}$	$2^{33.50}$	$2^{21.50}$	$2^{21.00}$	$2^{21.00}$

Summary: In order to reconstruct the complete 128-bit key $k_0 \parallel k_1$ it is sufficient to inject approximately 3 – 4 faults.

Outlook

Q: Can we apply Multi-Stage Fault Attacks to other ciphers?

A: Yes, indeed we can!

- We constructed an algorithm that can be used to analyse (SPN) block ciphers having independent subkeys using Multi-Stage Fault Attacks.
- Showed applications to PRINCE (this talk) and LED-128.
- To appear soon. (hopefully :-)

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Fin

Thank you for your attention!