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Information-Combining Differential Fault Attacks on DEFAULT

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Eurocrypt 2022

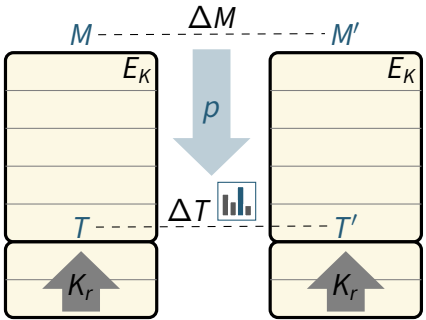
Outline

- Background
- Attacks on Simple Key Schedule
- Equivalent Keys
- Attacks on Strong Key Schedule

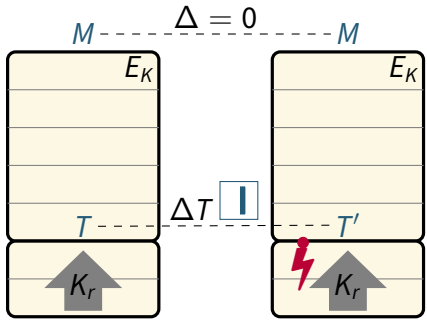
Background

How `DEFAULT` protects against DFA

Differential Fault Attacks (DFA)

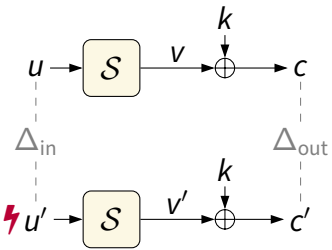


differential cryptanalysis



differential fault attacks

Differential Fault Attacks (DFA)



- Transition $\Delta_{\text{in}} \rightarrow \Delta_{\text{out}}$ limits (u, v) and k.
- $\text{DDT}[\Delta_{\text{in}}, \Delta_{\text{out}}]$ defines number of solutions.
- Thus, small entries benefit attacker.

DEFAULT

- Design Strategy by Baksi et al. at ASIACRYPT 2021 [BBB+21b]
- Intrinsic resistance against DFA thanks to special S-boxes with linear structures
- Block Cipher DEFAULT:
  - 128-bit classical security
  - 64-bit DFA security
  - simple [BBB+21a], and strong key schedule [BBB+21b]

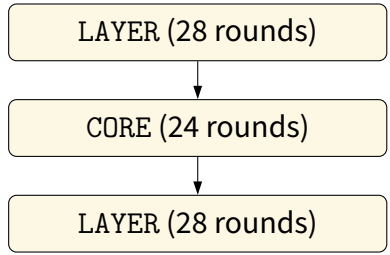


Figure: Design of DEFAULT

DEFAULT

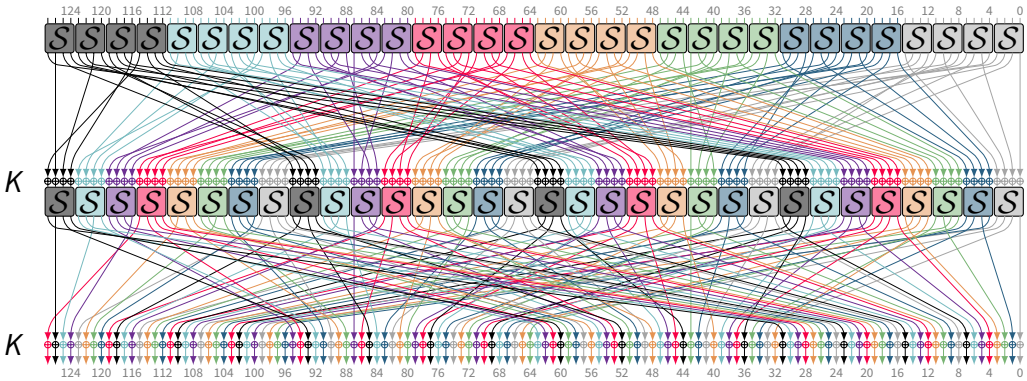
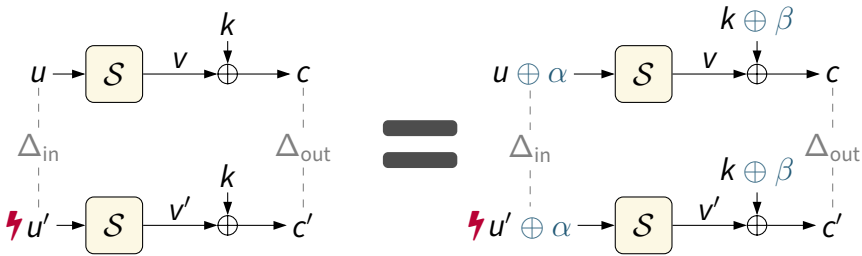


Figure: Two rounds of DEFAULT-LAYER, illustrating the S-box grouping.

Table: Differential Distribution Table of the S-box $\mathcal{S}$ with linear structures

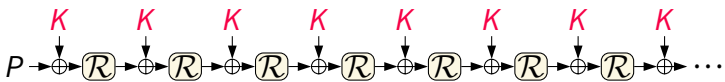
$\Delta_{in} \backslash \Delta_{out}$	0	1	2	3	4	5	6	7	8	9	a	b	c	d	e	f
0	**16**	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
1	·	·	·	8	·	·	·	·	·	8	·	·	·	·	·	·
2	·	·	·	·	·	·	·	8	·	·	·	·	·	8	·	·
3	·	·	·	·	8	·	·	·	·	·	·	·	·	·	8	·
4	·	·	·	·	·	·	·	8	·	·	·	·	·	8	·	·
5	·	·	·	·	8	·	·	·	·	·	·	·	·	·	8	·
6	·	·	·	·	·	·	·	·	·	·	**16**	·	·	·	·	·
7	·	·	·	8	·	·	·	·	·	8	·	·	·	·	·	·
8	·	·	·	·	·	·	8	·	·	·	·	·	8	·	·	·
9	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	**16**
a	·	8	·	·	·	·	·	·	·	·	·	8	·	·	·	·
b	·	·	8	·	·	·	·	·	8	·	·	·	·	·	·	·
c	·	8	·	·	·	·	·	·	·	·	·	8	·	·	·	·
d	·	·	8	·	·	·	·	·	8	·	·	·	·	·	·	·
e	·	·	·	·	·	·	8	·	·	·	·	·	8	·	·	·
f	·	·	·	·	·	**16**	·	·	·	·	·	·	·	·	·	·

DFA: Effect of Linear Structures [BBB+21b]



- Each linear structure $\alpha \to \beta$ leads to indistinguishable keys.
- If k is a valid key so is $k \oplus \beta$ (defining an affine space).
- 4 linear structures per S-box $\to 4^{32} = 2^{64}$ candidates

Attacks on Simple Key Schedule



Attack on Simple Key Schedule

- Intuition behind simple key schedule: learn same information each round
- Combine (linear) information across rounds
- Three step attack
  1. Attack 1 round $\rightarrow 2^{64}$ keys remain
  2. Attack 2 rounds $\rightarrow 2^{32}$ keys remain
  3. Attack 3 rounds $\rightarrow 2^{16}$ keys remain

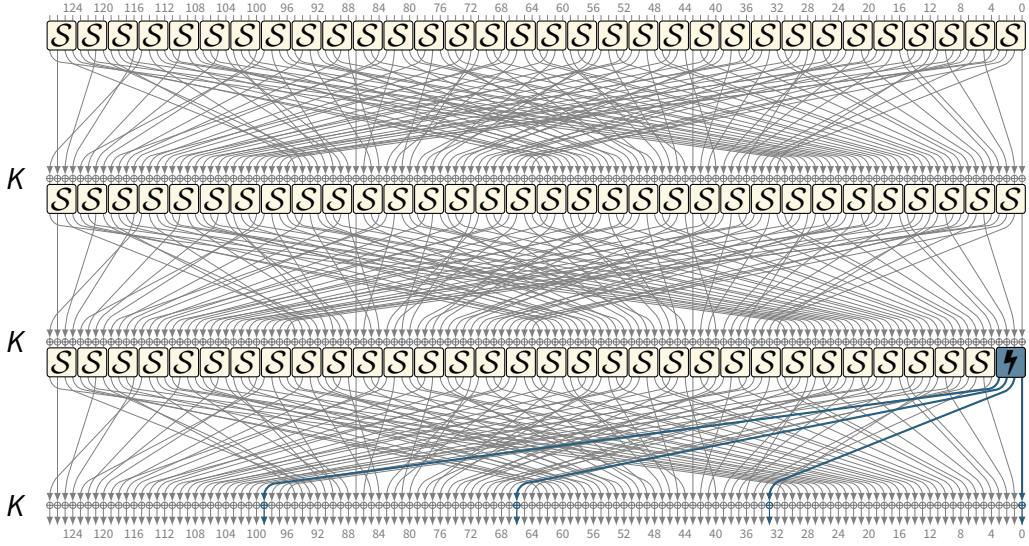


Figure: Attack on Simple Key Schedule (Step 1: 2^{64} keys remain)

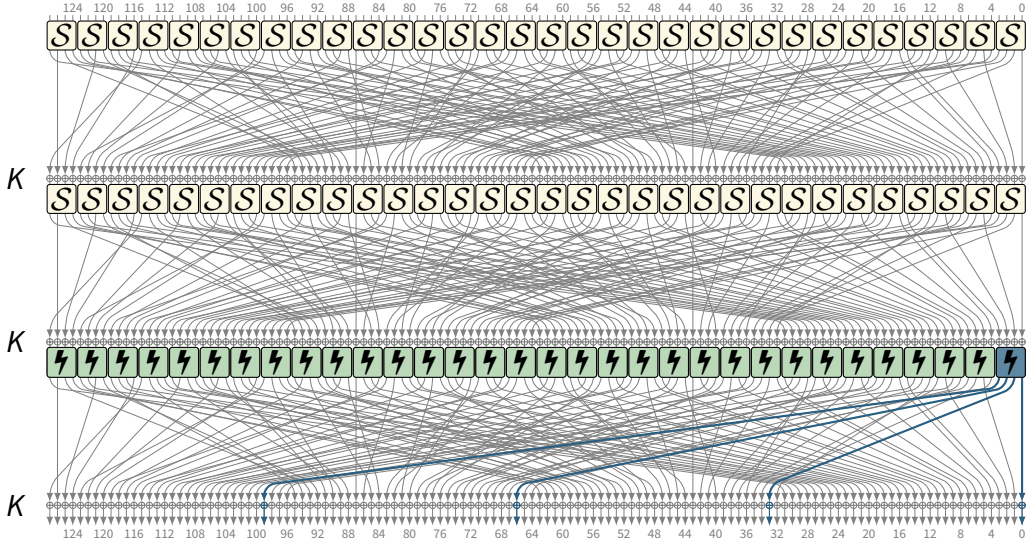


Figure: Attack on Simple Key Schedule (Step 1: 2^{64} keys remain)

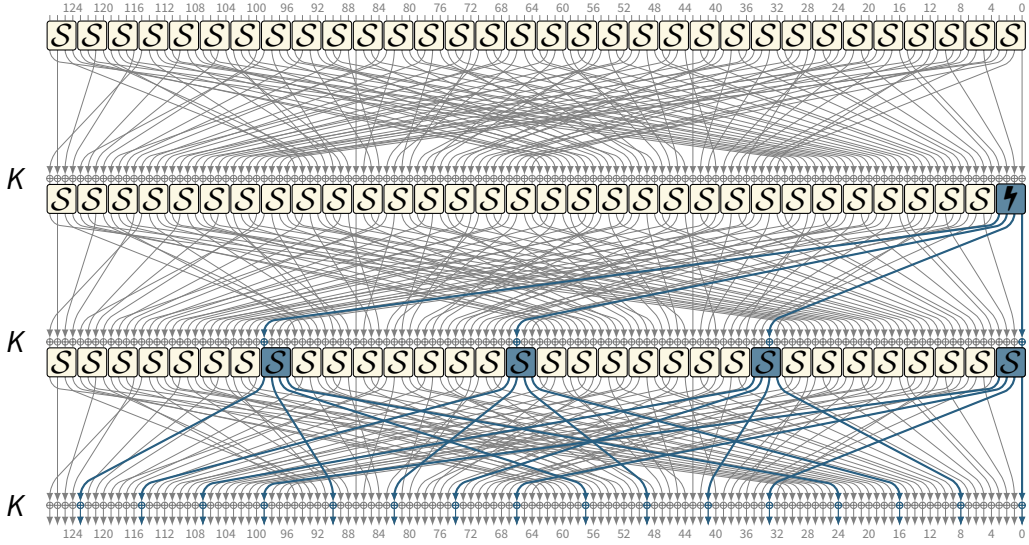


Figure: Attack on Simple Key Schedule (Step 2: 2^{32} keys remain)

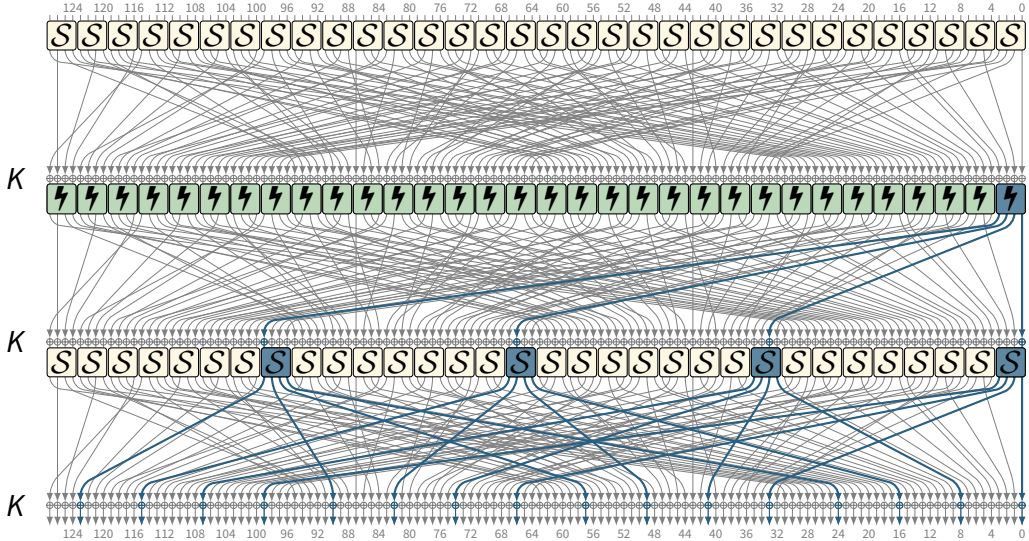


Figure: Attack on Simple Key Schedule (Step 2: 2^{32} keys remain)

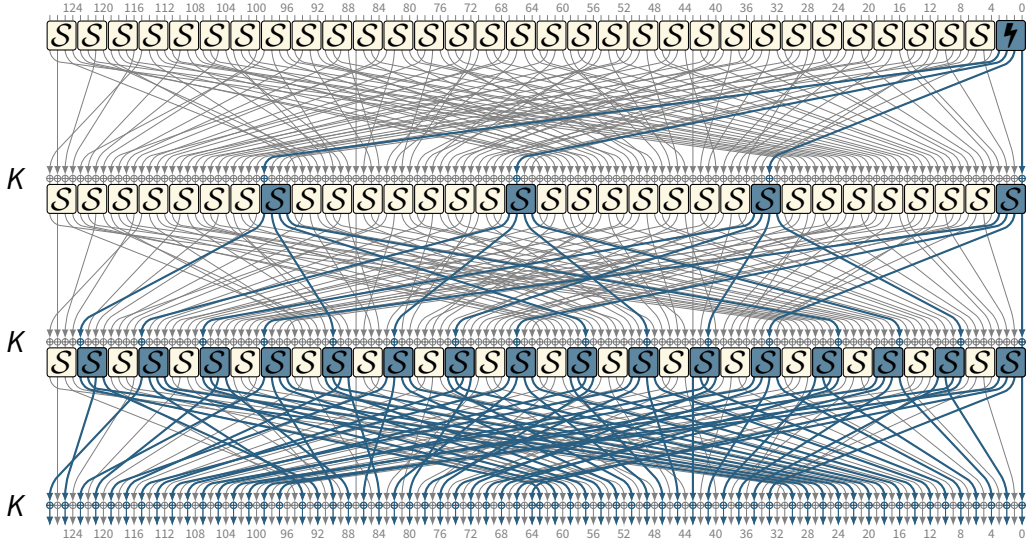


Figure: Attack on Simple Key Schedule (Step 3: 2^{16} keys remain)

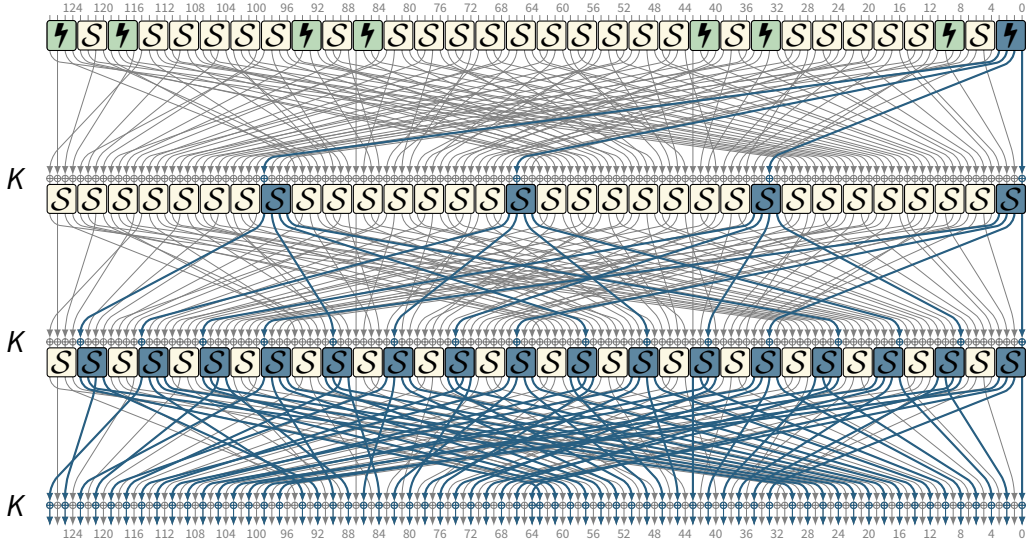


Figure: Attack on Simple Key Schedule (Step 3: 2^{16} keys remain)

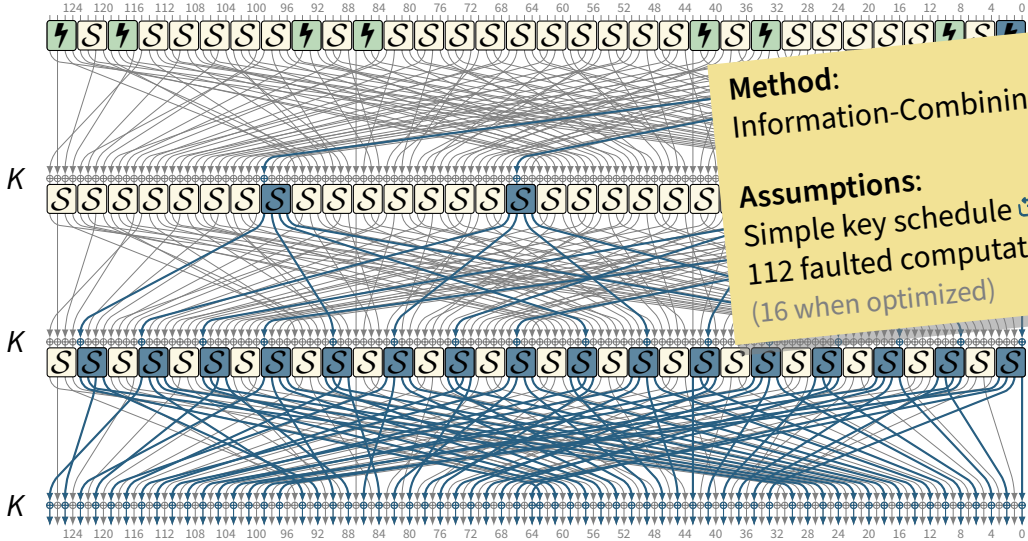


Figure: Attack on Simple Key Schedule ↻ (Step 3: 2^{16} keys remain)

Equivalent Keys

What if consecutive keys are independent?

Recall: Effect of Linear Structures [BBB+21b]

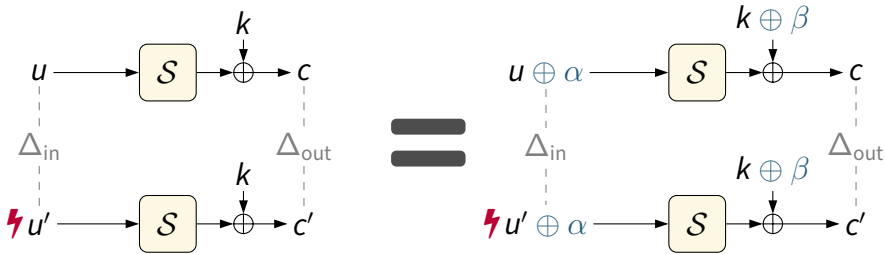


Figure: Each Linear Structure $\alpha \to \beta$ leads to indistinguishable keys

Linear Structures Imply Equivalent Keys

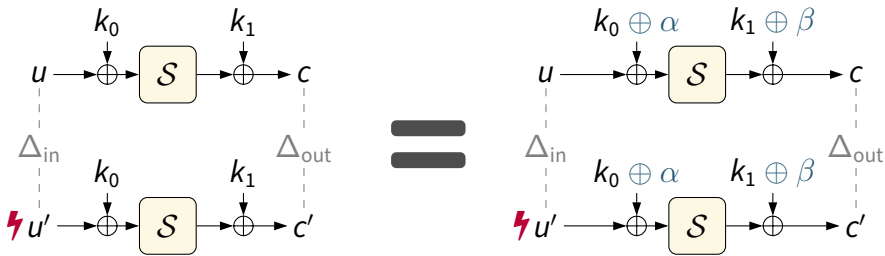


Figure: Each Linear Structure $\alpha \to \beta$ leads to equivalent keys

Equivalent Keys: Multiple Rounds

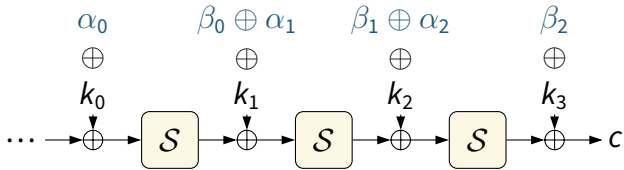


Figure: Equivalent keys for a toy cipher.

- Group keys into equivalence classes, each corrsponding to identical behavior.
- Idea: Pick a representative $\bar{k}$ from each equivalence class

Normalized Keys

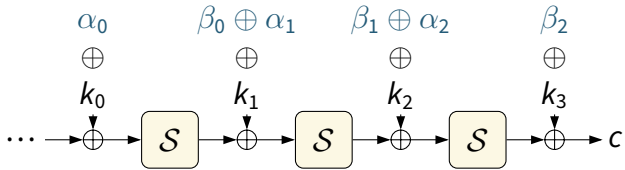


Figure: Equivalent keys for a toy cipher.

? How to pick representatives?

Reduce candidates for initial key guesses

For n round keys, $n - 1$ normalized keys can be recovered uniquely

Equivalent Keys in DEFAULT

- 4 linear structures $\alpha \to \beta$ per S-box
  - $0 \to 0, \quad 6 \to a, \quad 9 \to f, \quad f \to 5$
- 2^{64} linear structures per round
- For n independent keys
  - There are 2^{128n} keys
  - but we get 2^{64n+64} equivalence classes (distinct keyed permutations)

Example: DEFAULT

K_0 : 922d8799645a197240612627adac008c
K_1 : fd034fb83d3f82087ecb3d36ebd5b311
K_2 : 6c6ebe434de58a603140168a0cbcea2f
K_3 : ab6472a5fc49ba97a6504da4acaa8113

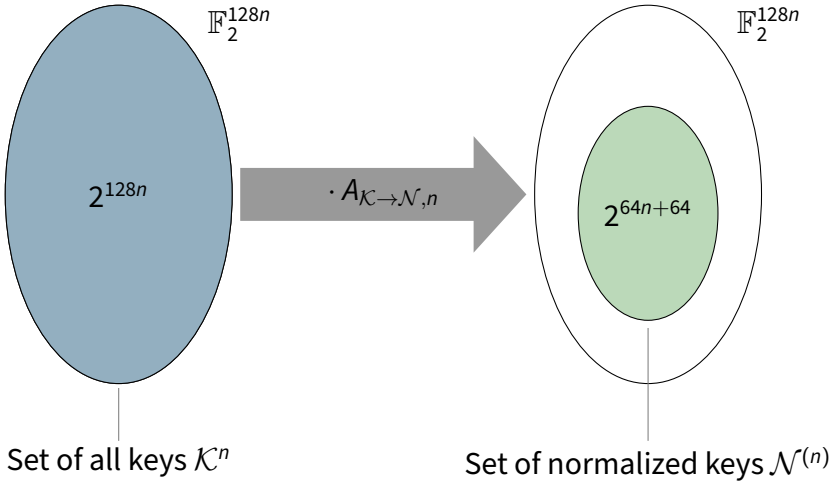
(a) Sequence of round keys K.

$\bar{K}_0$: 02221100023310122001202132330013
$\bar{K}_1$: 22312310332022020103310210031312
$\bar{K}_2$: 31012322123322300020111133332110
$\bar{K}_3$: 1f95f3c6f75987f847a46938a2ea468c

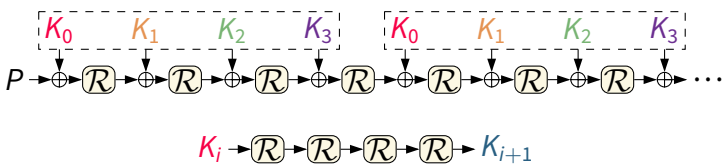
(b) Equivalent normalized key $\bar{K}$.

Figure: Sequence of round keys and its normalized equivalent.

Normalizing Keys is a Linear Operation

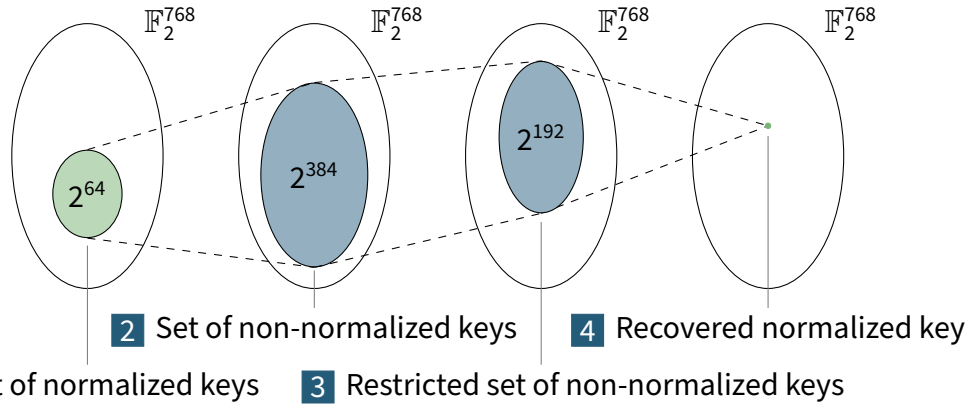


Attacks on Strong Key Schedule



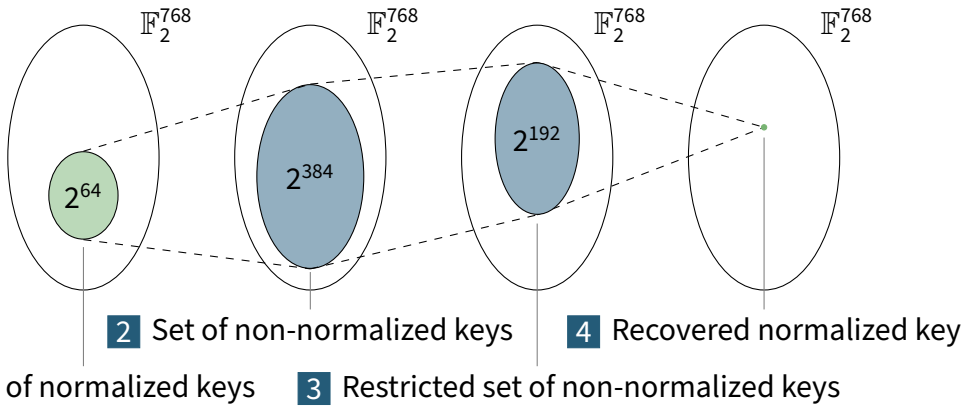
Linear Spaces in the Attack on DEFAULT-LAYER

- Pretend there are 6 independent keys $K_0, \ldots, K_5$



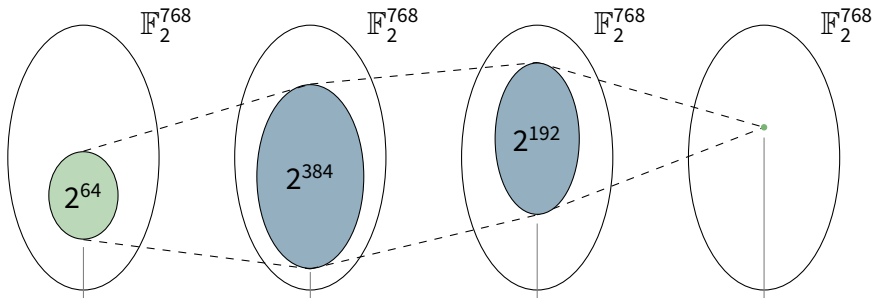
Linear Spaces in the Attack on DEFAULT-LAYER

1 Recover 2^{64} normalized keys $\bar{K}_0, \ldots, \bar{K}_5$ using DFA



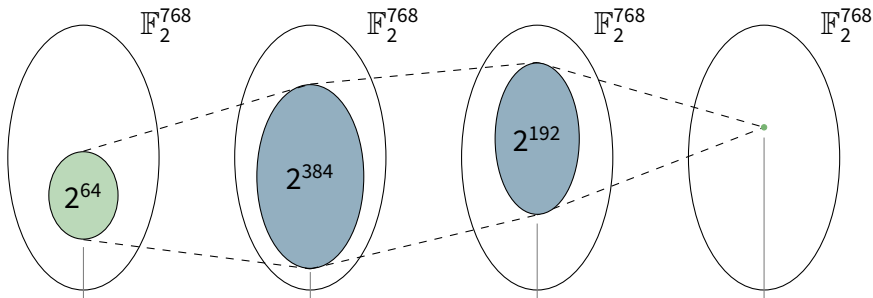
Linear Spaces in the Attack on DEFAULT-LAYER

2 Convert to linear space of non-normalized keys



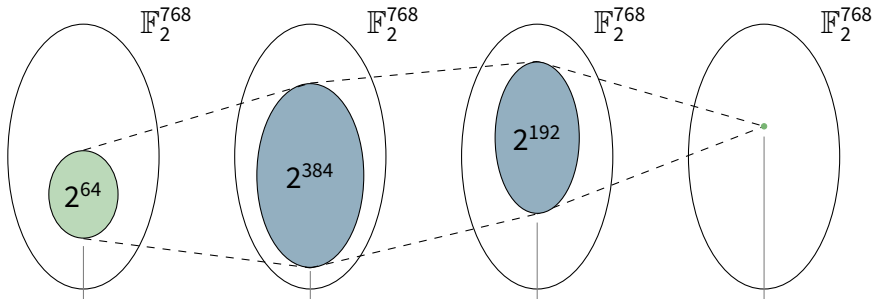
Linear Spaces in the Attack on DEFAULT-LAYER

3 Add condition that $K_0 = K_4$ and $K_1 = K_5$



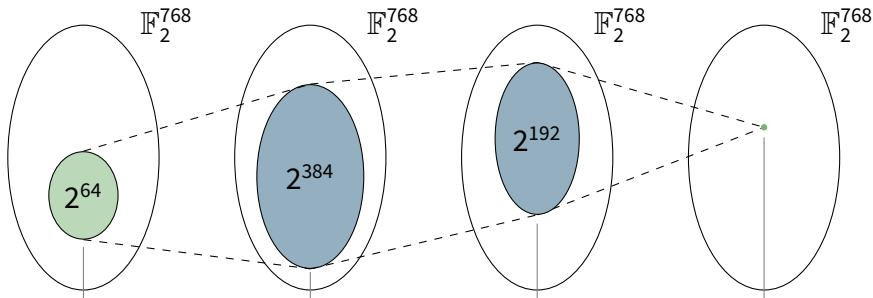
Linear Spaces in the Attack on DEFAULT-LAYER

4 Normalize the remaining keys to get a single key



Linear Spaces in the Attack on DEFAULT-LAYER

5 Attack DEFAULT-CORE using classical DFA

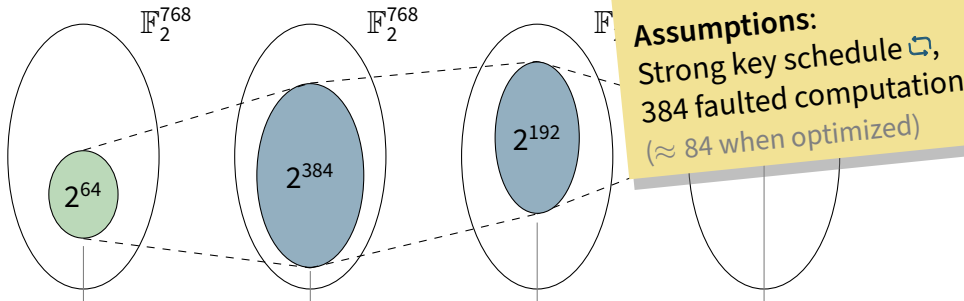


Linear Spaces in the Attack on DEFAULT-LAYER

Method:
Normalized Keys,
Information-Combining

Assumptions:
Strong key schedule ↻,
384 faulted computations
(≈ 84 when optimized)

5 Attack DEFAULT-CORE using classical DFA



Summary of Attacks on DEFAULT-LAYER

Approach	Faults	Time	Key Schedule		
			simple	strong	ideal
DFA [BBB+21b]	64	2^{64}	⏳	⏳	
Enc-Dec IC-DFA	16	$\leq 2^{39}$	✓		
Multi-round IC-DFA	16	$\leq 2^{20}$	✓		
Generic NK DFA	1728	2^{0}	✓	✓	✓
Enc-Dec IC-NK-DFA	288	2^{32}	✓*	✓	
Multi-round IC-NK-DFA	84 ± 15	2^{0}	✓*	✓	

Conclusion

- `DEFAULT` is an interesting concept to provide cipher-level fault resistance
- Cipher-level protection against DFA remains an open problem
- Substantial ideas beyond linear structures seem to be necessary

- https://eprint.iacr.org/2021/1374
- https://extgit.iaik.tugraz.at/castle/tool/dfa_on_default

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Bibliography I

[BBB+21a] Anubhab Baksi, Shivam Bhasin, Jakub Breier, Mustafa Khairallah, Thomas Peyrin, Sumanta Sarkar, and Siang Meng Sim. **DEFAULT: Cipher Level Resistance Against Differential Fault Attack**. IACR Cryptology ePrint Archive, Report 2021/712. 2021. URL: https://eprint.iacr.org/2021/712/20210528:092448.

[BBB+21b] Anubhab Baksi, Shivam Bhasin, Jakub Breier, Mustafa Khairallah, Thomas Peyrin, Sumanta Sarkar, and Siang Meng Sim. **DEFAULT: Cipher Level Resistance Against Differential Fault Attack**. ASIACRYPT 2021. Vol. 13091. LNCS. Springer, 2021, pp. 124–156.

Table: Information learned when injecting a fault Δ_{in} / Δ_{out}.

Δ_{in}	Learned expression (Enc)	Δ_{out}	Learned expression (Dec)
0	1	0	1
1	$k_0 \oplus k_1 \oplus k_2 \oplus k_3$	1	$k_0 \oplus k_1 \oplus k_2 \oplus k_3$
2	$k_0 \oplus k_2$	2	$k_0 \oplus k_3$
3	$k_1 \oplus k_3$	3	$k_1 \oplus k_2$
4	$k_0 \oplus k_2$	4	$k_0 \oplus k_1 \oplus k_2 \oplus k_3$
5	$k_1 \oplus k_3$	5	1
6	1	6	$k_1 \oplus k_2$
7	$k_0 \oplus k_1 \oplus k_2 \oplus k_3$	7	$k_0 \oplus k_3$
8	$k_0 \oplus k_1 \oplus k_2 \oplus k_3$	8	$k_0 \oplus k_3$
9	1	9	$k_1 \oplus k_2$
a	$k_1 \oplus k_3$	a	1
b	$k_0 \oplus k_2$	b	$k_0 \oplus k_1 \oplus k_2 \oplus k_3$
c	$k_1 \oplus k_3$	c	$k_1 \oplus k_2$
d	$k_0 \oplus k_2$	d	$k_0 \oplus k_3$
e	$k_0 \oplus k_1 \oplus k_2 \oplus k_3$	e	$k_0 \oplus k_1 \oplus k_2 \oplus k_3$
f	1	f	1

Optimized Attack on Strong Key Schedule

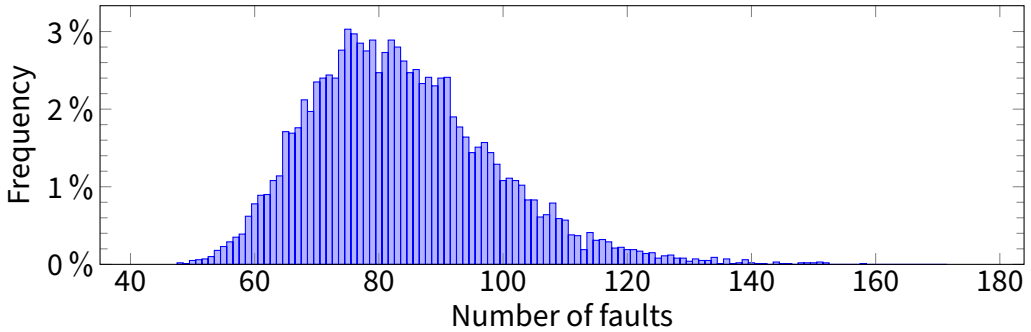

Figure: Number of faults needed to recover the key ($n = 10\,000$).