Analysis of Grain's Initialization Algorithm

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Outline

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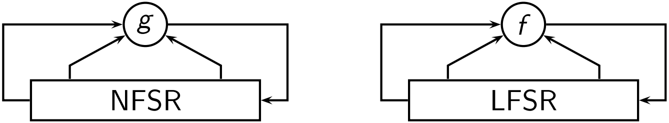
Grain

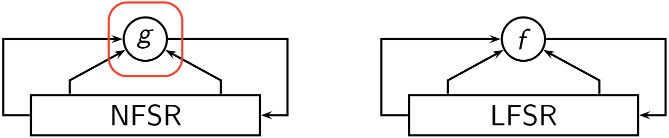
- Family of stream ciphers designed in 2005 by M.Hell, T. Johansson and W. Meier
- Has two members Grain v1 and Grain-128:
  - **Grain v1** accepts 80-bit key and 64-bit IV value
  - **Grain-128** accepts 128-bit key and 96-bit IV value
- One of 4 hardware ciphers in eSTREAM Portfolio

Keystream Generation



- **Grain v1:** 80-bit NFSR and 80-bit LFSR
- **Grain-128:** 128-bit NFSR and 128-bit LFSR

Keystream Generation



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- **Grain-128:** $g(x_1 \ldots x_{19})$ is a very sparse quadratic function

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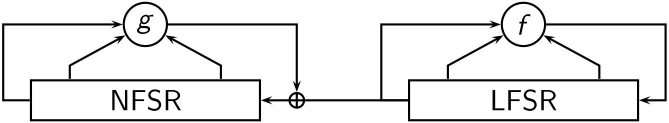

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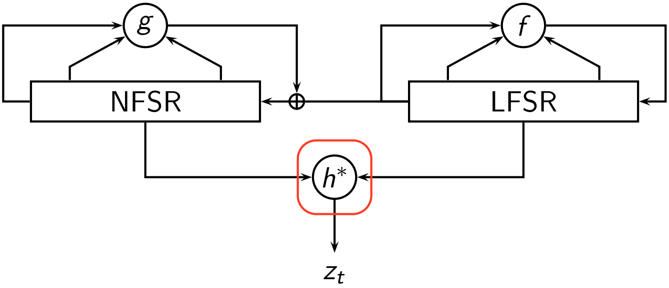
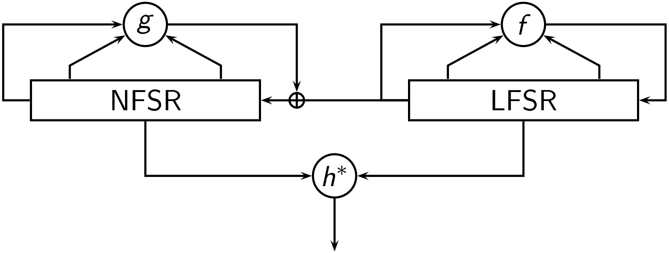


- **Grain v1:** $h^*(x_1 \ldots x_{12})$ is a function of degree 3
- **Grain-128:** $h^*(x_1 \ldots x_{17})$ is a function of degree 3

Key and IV Initialization



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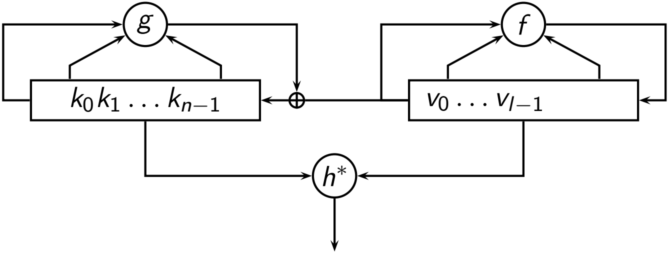

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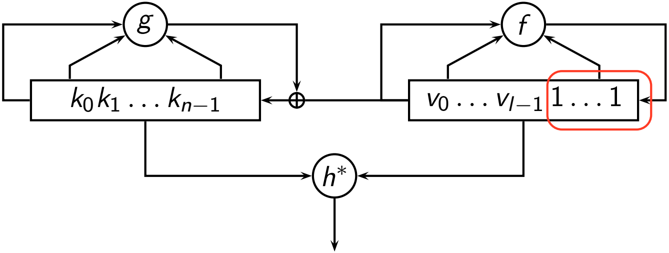

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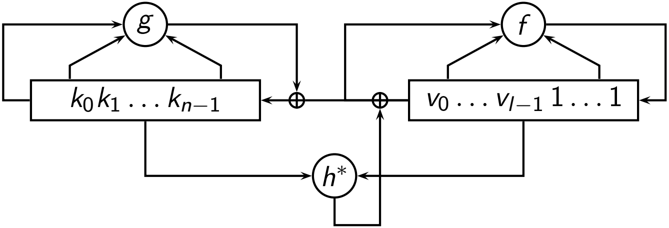


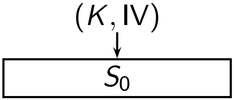
- **Grain v1:** 160 initialization rounds
- **Grain-128:** 256 initialization rounds

Outline

Slide Attacks

- Introduced by A. Biryukov and D. Wagner in 1999
- Mainly used to attack block ciphers
- Exploits the self-similarity of the rounds of a cipher
- Complexity is not affected by the number of rounds

Slid Pairs in Stream Ciphers



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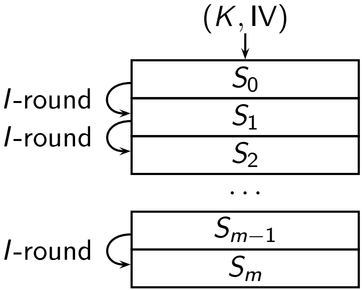

(initialization rounds)

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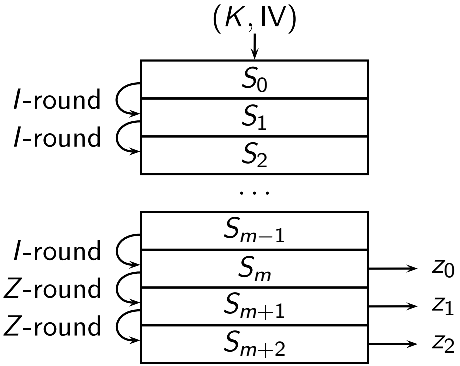

(initialization rounds)

(keystream generation)

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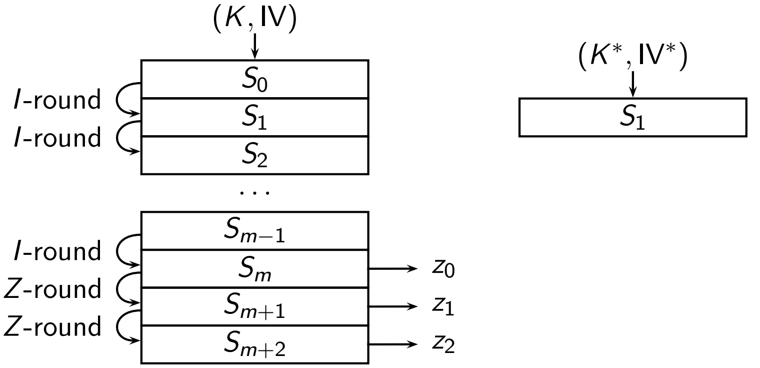

- **Condition 1:** S_1 is the initial state of a pair (K^*, IV^*)

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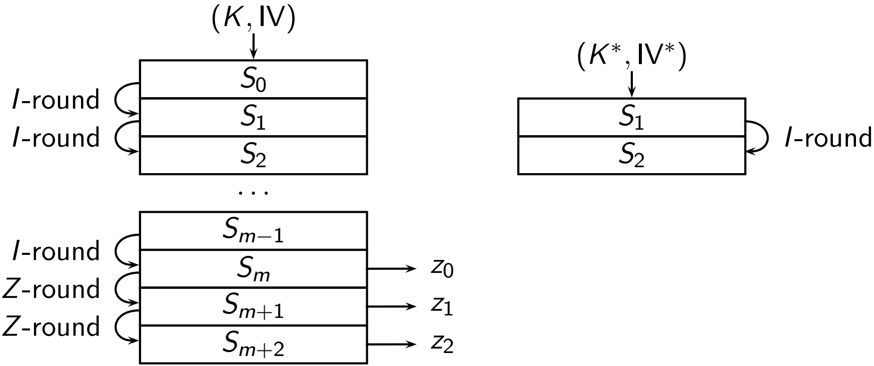

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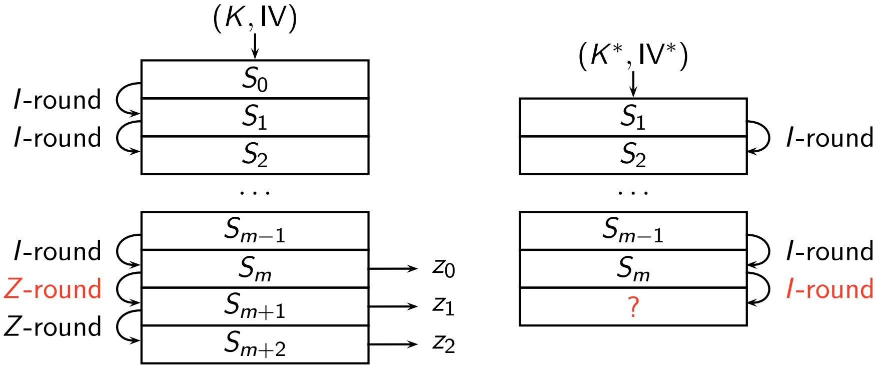

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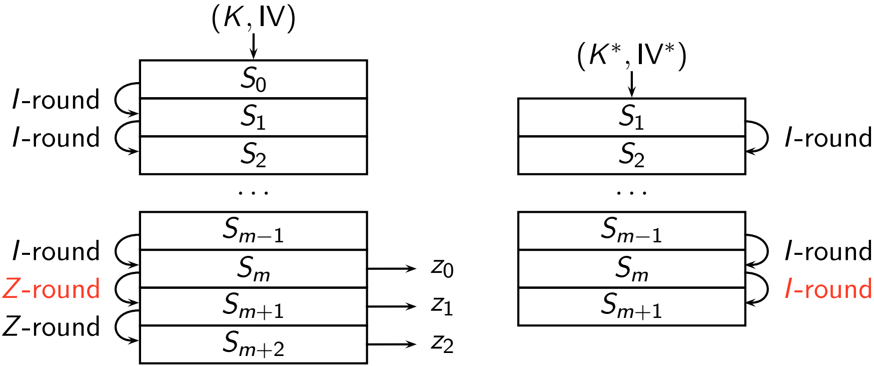

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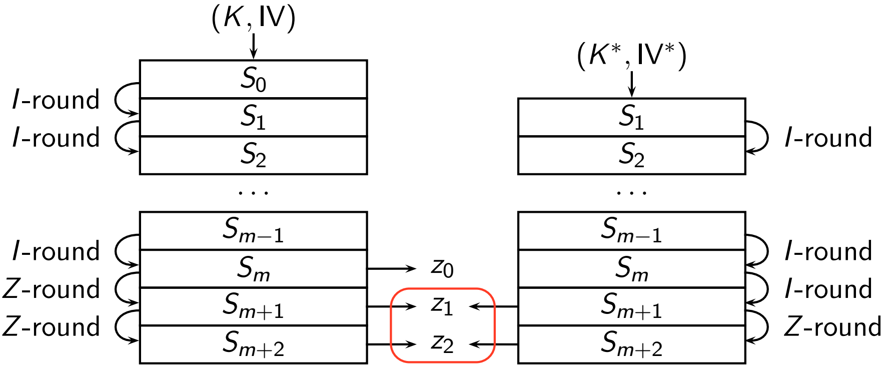

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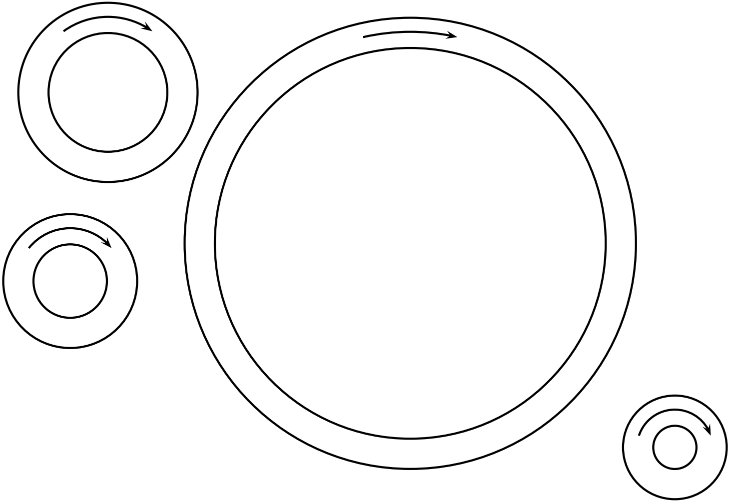
$\Rightarrow$ Difference in right-most bit of NFSR and LFSR
$\Rightarrow$ Only affects output stream after 16 (32) steps
$\Rightarrow$ First 15 (31) keystream bits are still equal (but shifted)

Related (K, IV) Pairs in Grain

Property

For a fraction $2^{-2 \cdot n}$ of pairs (K, IV), there exists a related pair (K^*, IV^*) which produces an identical but n-bit shifted key stream.

Is This Surprising?



2^{160} possible states form cycles

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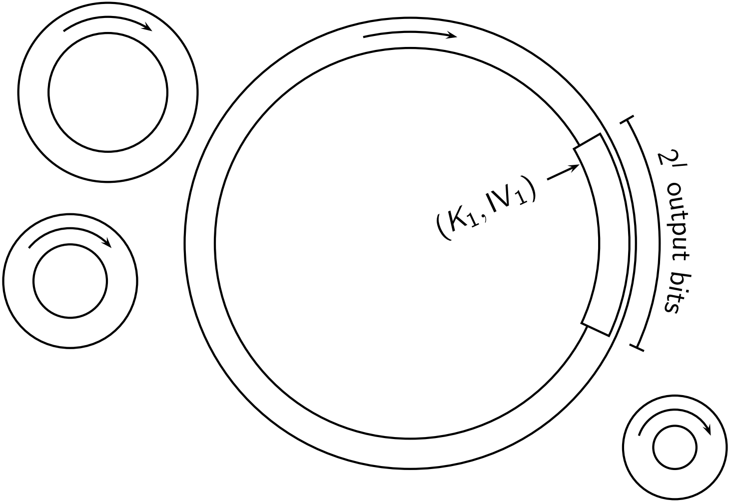

initialization algorithm defines starting point

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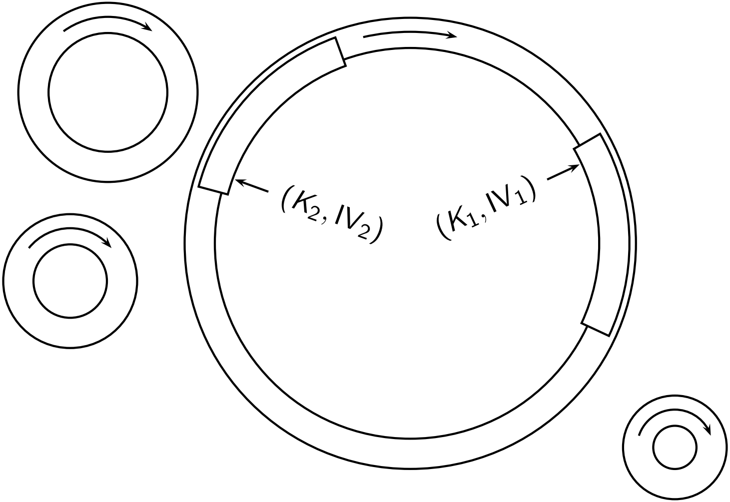

$2^{80} \times 2^{64}$ starting points

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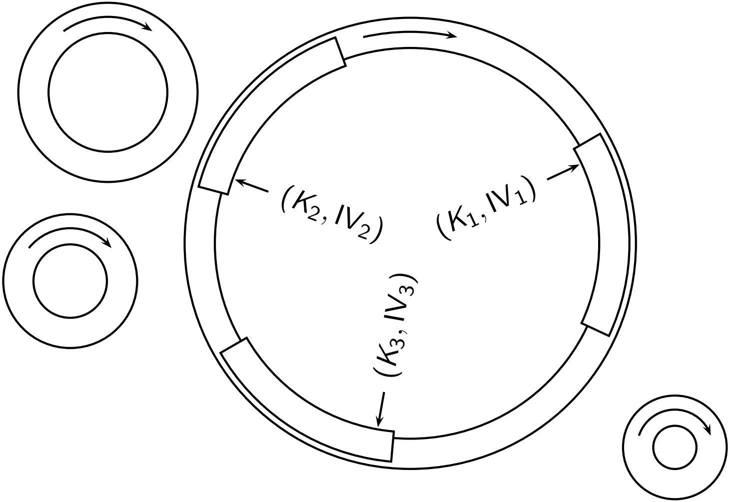

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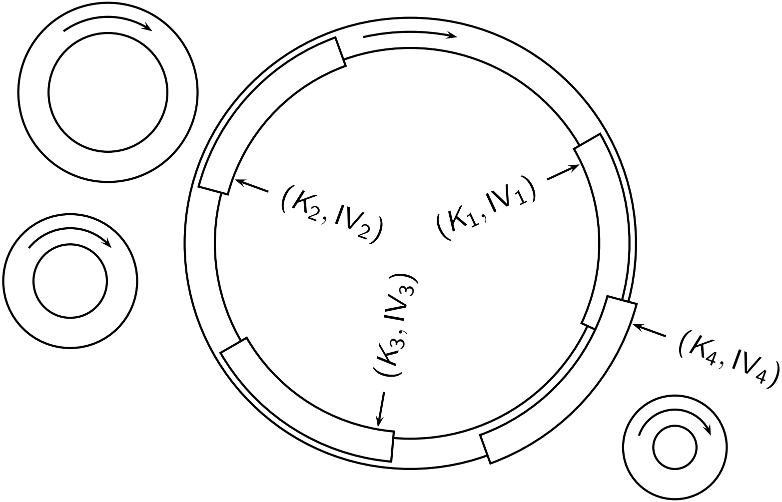

if $2^{80} \times 2^{64} \times 2^{l} > 2^{160}$ $\longrightarrow$ overlap unavoidable

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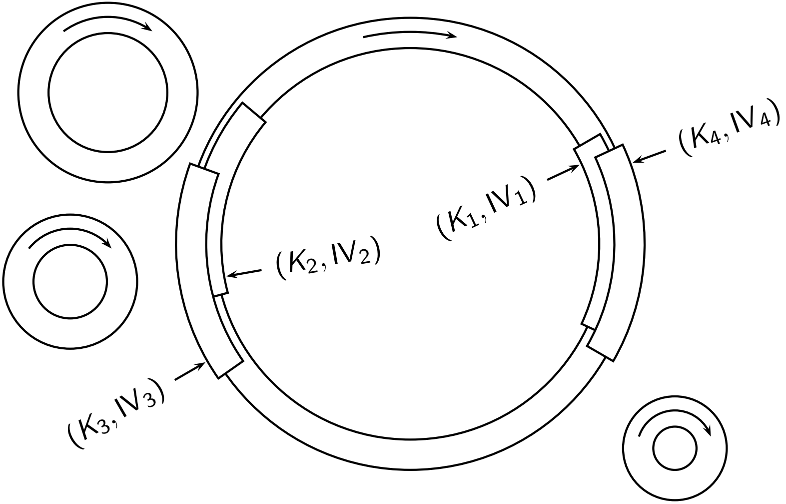

special feature of Grain: clustering of starting points

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Related Key Attack

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  - $\Rightarrow$ With probability $1/4$, sequences are identical but shifted
  - $\Rightarrow$ This indicates that $s_{80} = 1$, which yields simple (non-linear) equation in secret key bits
- Unlikely to happen in practice, unless
  - Session keys are derived from master key in funny way
  - Adversary can cause synchronization errors

Speeding up Exhaustive Search when $IV = [1 \ldots 1]$

$k_0 \ldots k_{78} k_{79}$	$1 \ldots 1 \quad 1 \quad 1$

initialize Grain with arbitrary key K

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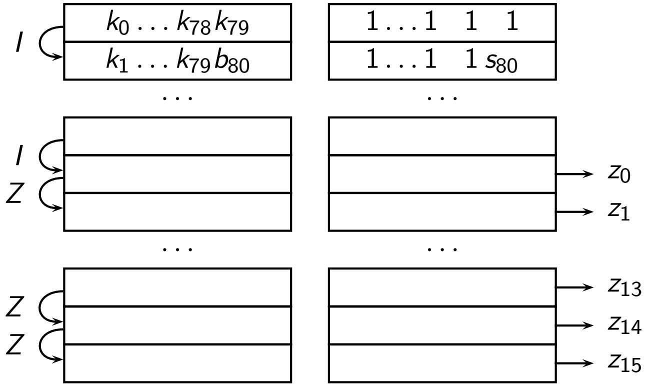

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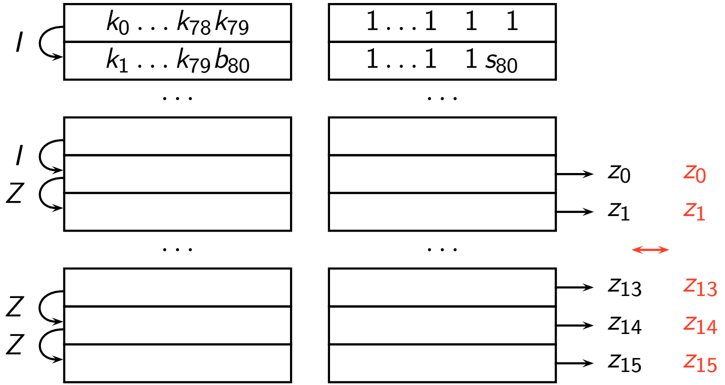

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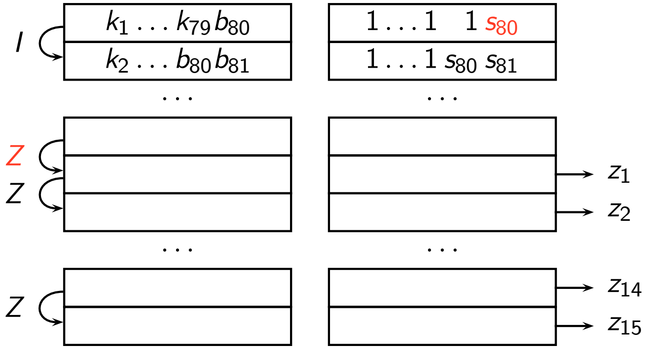

if no match, shift everything up by one step

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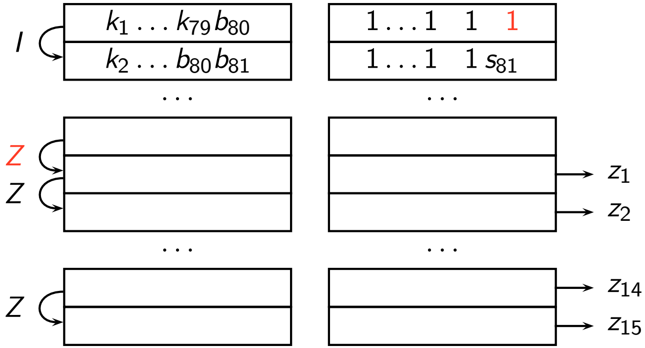

if $S_{80} = 1 \Rightarrow$ no need to recompute anything

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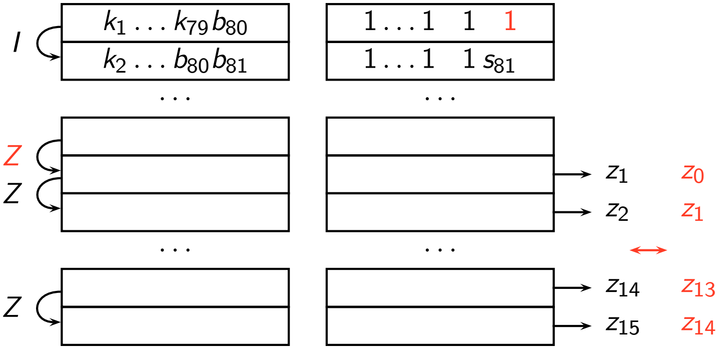

compare (shifted) output with known keystream

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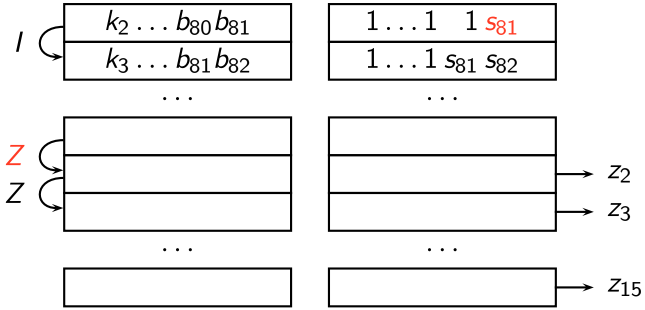

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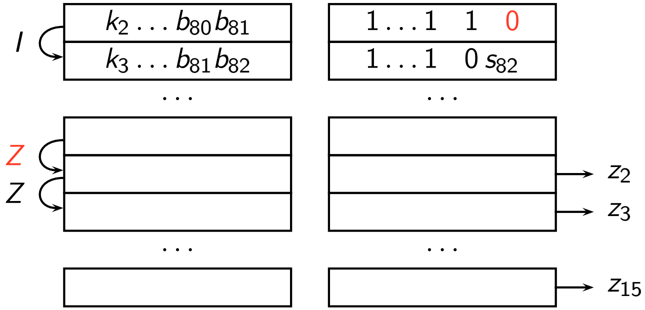

if $S_{81} = 0 \Rightarrow$ correct and rerun initialization

Speeding up Exhaustive Search when $IV = [1 \dots 1]$

$k_0 \dots b_{80} b_{81}$	$1 \dots 1 \quad 1 \quad 1$

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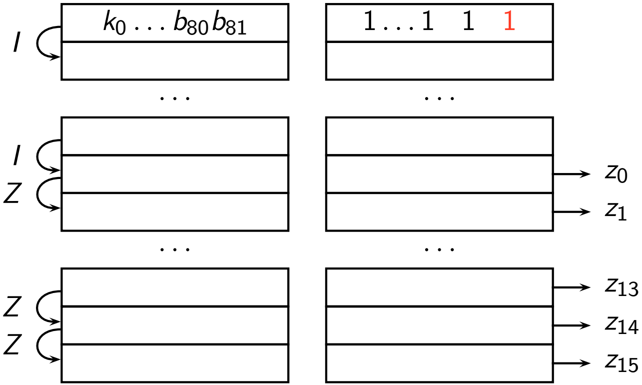

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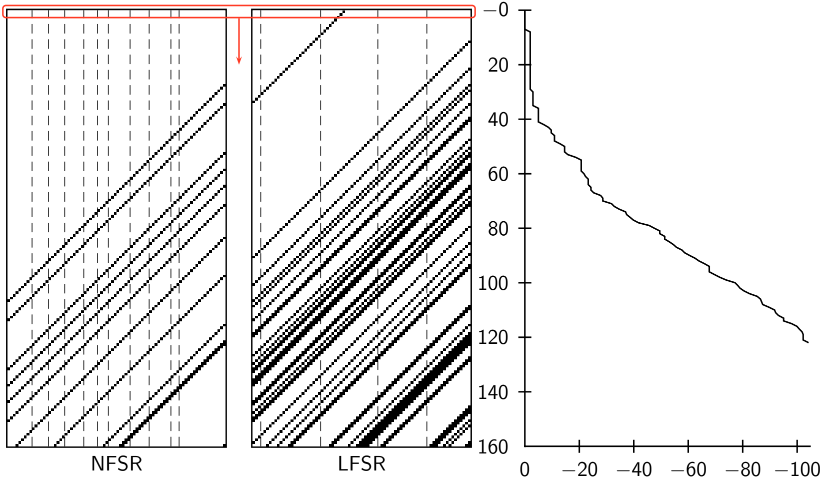
  $\Rightarrow$ twice as fast as regular exhaustive search
- Only works when $IV = [1 \ldots 1]$

Outline

Sparse Characteristics in Grain

- Start with a single bit difference in the state at step t
- Propagate backwards and forwards
- Each time a difference enters the non-linear functions we have to make a choice
  - $\longrightarrow$ **Our approach:** choose the difference which introduces as few differences as possible in the next steps and in particular in NFSR

Illustration – Grain v1



single bit difference at step 0

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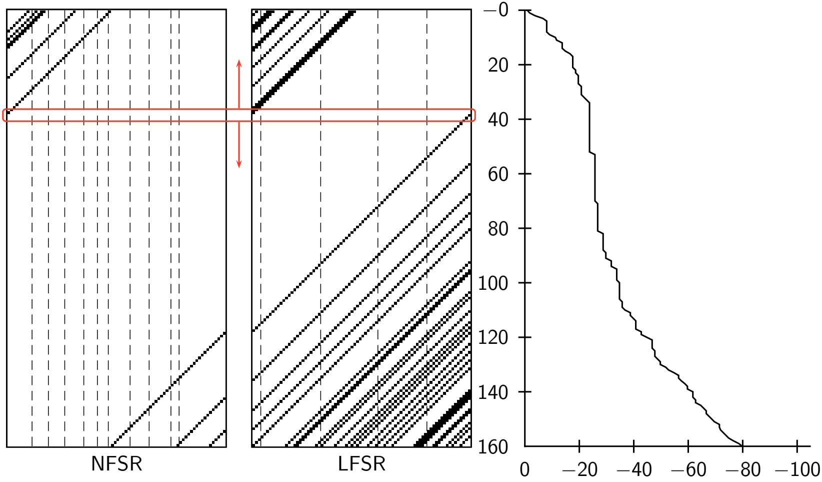

single bit difference at step 38

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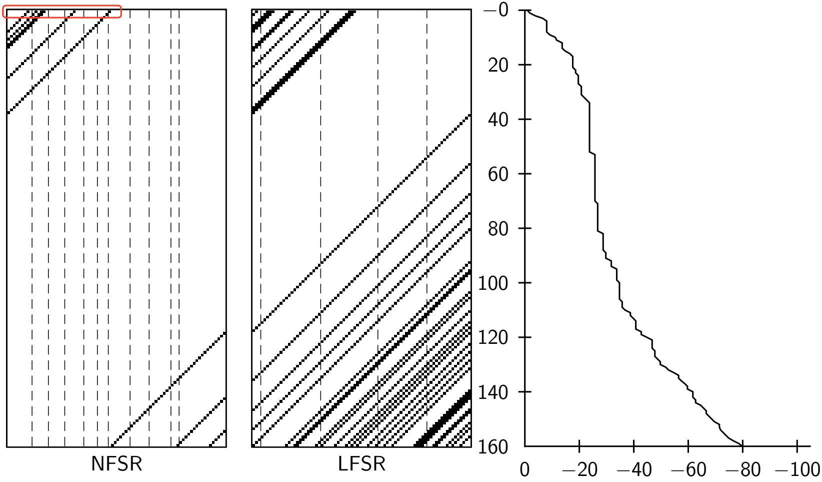

differences in NFSR at step 0 → related keys

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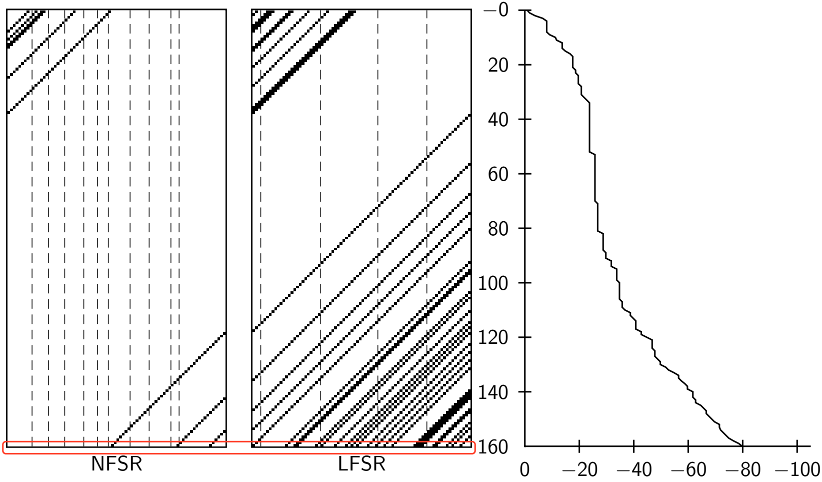
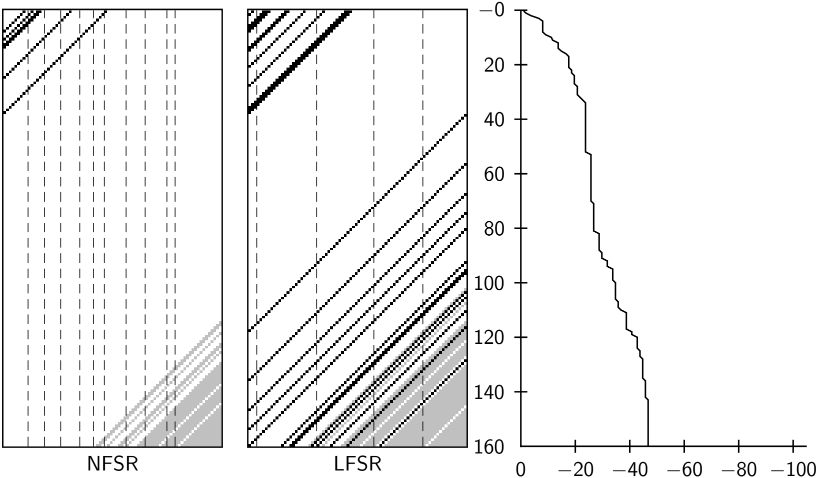


equalities in final state → equalities in a few keystream positions

Truncated Differentials



focus on first keystream position; ignore rest

Data Complexity

- Keystream can be distinguished from random by initializing with N different related pairs (K, IV_i) and $(K + K', \mathrm{IV}_i + \mathrm{IV}')$, and counting number of 0- and 1-differences in z_0.
- How large should N be to observe a bias?

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- How large should N be to observe a bias?
  - $p_C = P(\text{characteristic is followed}) = 2^{-47}$
  - $p_R = P(\text{equality in } z_0 \text{ in random case}) = 1/2$

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- How large should N be to observe a bias?
  - $p_C = P(\text{characteristic is followed}) = 2^{-47}$
  - $p_R = P(\text{equality in } z_0 \text{ in random case}) = 1/2$
- **Regular differential attack:** $p_C \gg p_R$

  $\Rightarrow N > 1/p_C$
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  $= 2^{94} \gg 2^{63}$ (total number of possible IV pairs)

Outline

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- Split characteristic into two parts:
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$\Rightarrow$ **Effect:** reduces N from $(p_1 p_2)^{-2}$ to $p_1'^{-1} p_2^{-2}$

Partitioning the Key and IV Space

	IV_1	IV_2	IV_3	IV_4	...					$IV_{2^{64}}$
K_1	1	0	1	1	1	1	...	0	0	1
K_2	1	0	1	0	1	1	...	0	0	0
K_3	0	0	1	0	1	1	...	0	0	0
K_4	1	1	1	1	0	0	...	0	1	1
K_5	1	0	1	0	1	1	...	1	1	0
K_6	1	0	0	1	0	1	...	0	1	0
$\vdots$	$\vdots$					$\vdots$		$\vdots$		
	0	1	0	0	0	1	...	1	1	0
	1	0	1	0	1	1	...	1	0	1
$K_{2^{80}}$	0	1	0	1	0	0	...	1	0	1

$F_t(K_i, IV_i)$ for differences K' and IV'

Partitioning the Key Space

	IV_1	IV_2	IV_3	IV_4	...					$IV_{2^{64}}$
K_a	0	0	0	0	0	0	...	0	0	0
⋮	⋮					⋮		⋮		
K_c	0	0	0	0	0	0	...	0	0	0
K_d	0	1	1	0	0	1	...	1	0	0
⋮	⋮					⋮		⋮		
	0	1	1	0	0	1	...	1	0	0
	⋮					⋮		⋮		
	1	0	1	0	1	1	...	1	0	1
	⋮					⋮		⋮		
	1	0	1	0	1	1	...	1	0	1

sorting rows $\longrightarrow$ equivalent key classes

Partitioning the Key Space

	IV_1	IV_2	IV_3	IV_4	…					$IV_{2^{64}}$
K_a	0	0	0	0	0	0	…	0	0	0
⋮	⋮					⋮		⋮		
K_c	0	0	0	0	0	0	…	0	0	0
K_d	0	1	1	0	0	1	…	1	0	0
⋮	⋮					⋮		⋮		
	0	1	1	0	0	1	…	1	0	0
	⋮					⋮		⋮		
	1	0	1	0	1	1	…	1	0	1
	⋮					⋮		⋮		
	1	0	1	0	1	1	…	1	0	1

weak keys

sorting rows → equivalent key classes

Partitioning the IV Space

	IV_a	…	IV_c	IV_d	…					
K_a	0	…	0	0	…	0	…	0	…	0
⋮	⋮									
K_c	0	…	0	0	…	0	…	0	…	0
K_d	0	…	0	1	…	1	…	0	…	0
⋮	⋮									
	0	…	0	1	…	1	…	0	…	0
	⋮		⋮	⋮		⋮		⋮		⋮
	0	…	0	1	…	1	…	1	…	1
	⋮									
	0	…	0	1	…	1	…	1	…	1

sorting columns $\rightarrow$ equivalent IV classes

Partitioning the IV Space

weak IVs (spanning from IV_d to the last column)

	IV_a	…	IV_c	IV_d	…		…		…	
K_a	0	…	0	0	…	0	…	0	…	0
⋮	⋮									
K_c	0	…	0	0	…	0	…	0	…	0
K_d	0	…	0	1	…	1	…	0	…	0
⋮	⋮									
	0	…	0	1	…	1	…	0	…	0
	⋮		⋮	⋮		⋮		⋮		⋮
	0	…	0	1	…	1	…	1	…	1
	⋮									
	0	…	0	1	…	1	…	1	…	1

sorting columns $\rightarrow$ equivalent IV classes

Partitioning the IV Space

	IV_a	…	IV_c	IV_d	…					
K_a	0	…	0	0	…	0	…	0	…	0
⋮	⋮									
K_c	0	…	0	0	…	0	…	0	…	0
K_d	0	…	0	1	…	1	…	0	…	0
⋮	⋮									
	0	…	0	1	…	1	…	0	…	0
	⋮		⋮	⋮		⋮		⋮		⋮
	0	…	0	1	…	1	…	1	…	1
	⋮									
	0	…	0	1	…	1	…	1	…	1

when t increases $\rightarrow$ number of classes increases

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- Assume that secret key is weak
- **Stage 1:**
  - Initialize Grain with N different weak related pairs
  - Count number of 0- and 1-differences in z_0
  - ⇒ Keep separate counters for each IV equivalence class
- **Stage 2:**
  - Guess key equivalence class and combine counters of all IV equivalence classes for which Part 1 is satisfied
  - If no bias is detected, discard guess

Computing N

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- Probability of Part 1 can be written as $p_1 = p_K \cdot p_{\mathrm{IV}} \cdot p'_1$
  - p_K: fraction of keys which are weak
  - p_{IV}: fraction of IVs which are weak
  - p'_1: probability that Part 1 is satisfied for weak key and IV

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  - p'_1: probability that Part 1 is satisfied for weak key and IV
- For given key class guess, $M = p'_1 \cdot N$ pairs satisfy Part 1
- In order to detect bias after Part 2:

$\Rightarrow$ $M > p_2^{-2} \Rightarrow N > {p'_1}^{-1} p_2^{-2}$

Outline

Attack Complexities

Cipher	v1	v1	128	128	128
Rounds	160	112	256	224	192
Related keys	yes	no	yes	no	no
# Weak keys	2^{71}	2^{80}	2^{87}	2^{126}	2^{126}
# Weak IVs	2^{57}	2^{63}	2^{84}	2^{93}	2^{93}
N	2^{55}	(2^{72})	2^{73}	(2^{96})	2^{35}
t	33	28	75	78	76
p_1	2^{-23}	2^{-3}	2^{-64}	2^{-6}	2^{-6}
p_2	2^{-24}	2^{-35}	2^{-31}	2^{-47}	2^{-17}
# Key classes	2^{22}	8	2^{27}	72	72
# IV classes	2^{21}	8	2^{32}	64	64

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$\Rightarrow$ Attacks have limited practical impact, but can nonetheless be considered as non-ideal behavior