Attacks against Filter Generators Exploiting Monomial Mappings

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Summary

Introduction : Stream ciphers

Linear Feedback Shift Registers

Monomial equivalence between filtered LFSR

Univariate correlation attacks

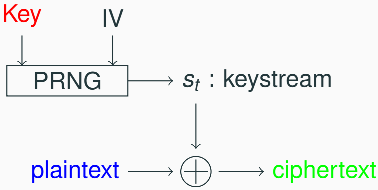
Impact on Boolean functions

Conclusions

Stream ciphers

Stream ciphers

- Symetric cryptography, $\neq$ block ciphers
- Based on Vernam cipher (one-time pad)
- PRNG



Stream ciphers

- Block cipher modes of operations (OFB, Counter)
- Specific design (LFSR, NLFSR)
- Internal state
- Large period
- A5/1 - A5/2, SNOW

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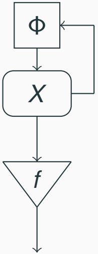
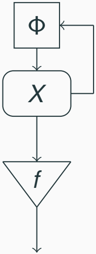
Interests

- Small latency
- No padding
- No error propagation
- Cheap

Generic attacks



- Key recovering



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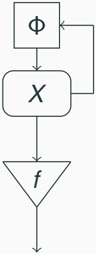

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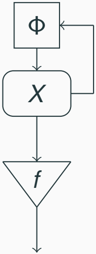

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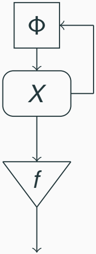

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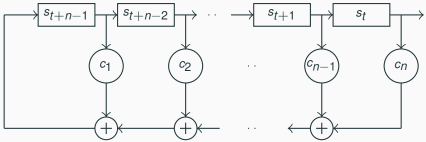
Always take an internal state twice bigger as the security level (i.e. key size)

LFSR

Linear feedback shift Register (LFSR)

Definition

Fibonacci representation



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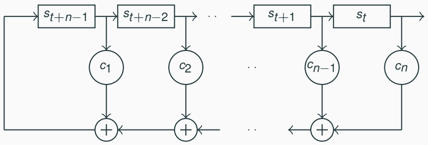
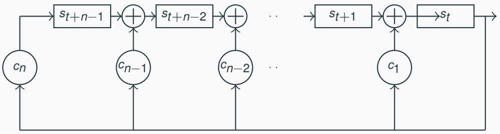


Definition

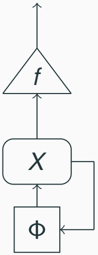
Gallois representation

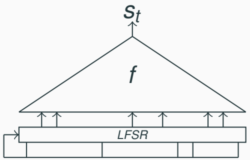


Classical properties of LFSR

- Nice statistical properties
- Linear
- $s_{t+L} = \sum_{i=1}^{n} c_i s_{t+n-i}, \forall t \leq 0$
- $P(X) = 1 - \sum_{i=1}^{n} c_i X^i$
- $P^*(X) = X^n P(1/X)$
- We wil take P primitive

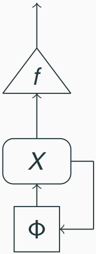
Filtered LFSR

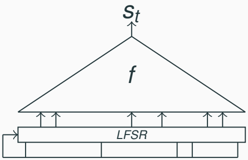




$$s_t = f(u_{t+\gamma_1}, \cdots, u_{t+\gamma_n})$$

Filtered LFSR





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Algebraic Normal Form

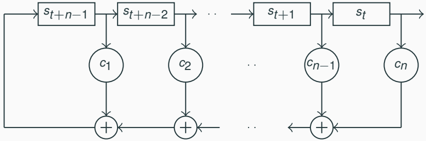
$$f(x_1, x_2, \cdots, x_n) = \sum_{u \in \mathbb{F}_2^n} a_u \prod_{i=1}^{n} x_i^{u_i}$$

$$= a_0 + a_1 x_1 + a_2 x_2 + \cdots + a_3 x_1 x_2 + \cdots + a_{2^n-1} x_1 \cdots x_n$$

Monomial equivalence

LFSR over a Finite Field

- α : root of the primitive characteristic polynomial in $\mathbb{F}_{2^n}$
- Identify the n-bit words with elements of $\mathbb{F}_{2^n}$ with the dual basis of $\{1, \alpha, \alpha^2, \cdots, \alpha^{n-1}\}$



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The state of the LFSR at time $(t+1)$ is the state of the LFSR at time t multiplied by α.

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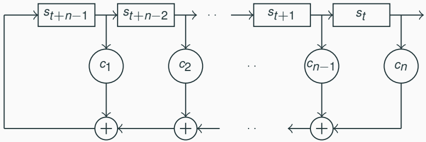

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For all t, $X_t = X_0\alpha^t$

Boolean functions

Proposition (Univariate representation)

$$F(X) = \sum_{i=0}^{2^n-1} A_i X^i$$

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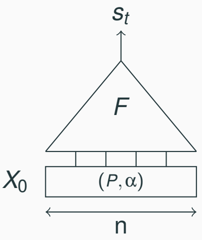
Monomial equivalence [Rønjom - Cid 2010]



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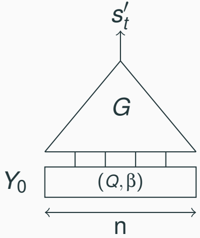

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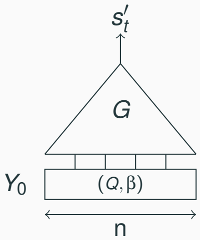

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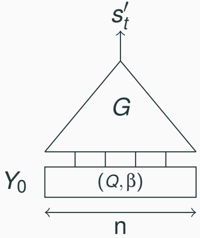

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$$\textbf{If } G(x) = F(x^r)$$
$$\textbf{with } rk \equiv 1 \mod (2^n - 1)$$
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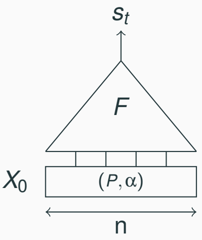

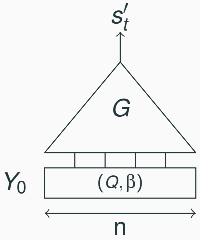

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If $G(x) = F(x^r)$

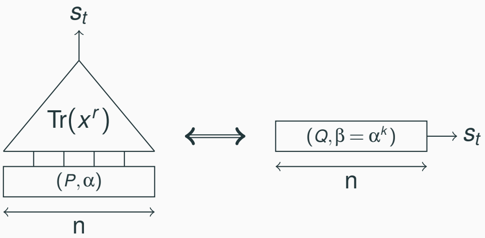
with $rk \equiv 1 \mod (2^n - 1)$

Then $s'_t = F(Y_0^r \alpha^t)$

For all t, $s'_t = s_t$ if $Y_0 = X_0^k$

Example

$F(x) = \mathrm{Tr}(x^r)$, with $\gcd(r, 2^n - 1) = 1$:
Let k be such that $rk \equiv 1 \mod (2^n - 1)$.



$\Longrightarrow$ The initial generator is equivalent to a plain LFSR of the same size.

Consequence

The security level of a filtered LFSR is the minimal security level for a generator of its equivalence class.

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- Algebraic attacks
- Correlation attacks

Algebraic attacks

Λ : Linear complexity

Proposition (Massey-Serconek 94)

Let an LFSR of size n filtered by a Boolean function F:

$$F(X) = \sum_{i=0}^{2^n-1} A_i X^i$$

Then

$$\Lambda = \#\{0 \leq i \leq 2^n - 2 : A_i \neq 0\}$$

Algebraic attacks

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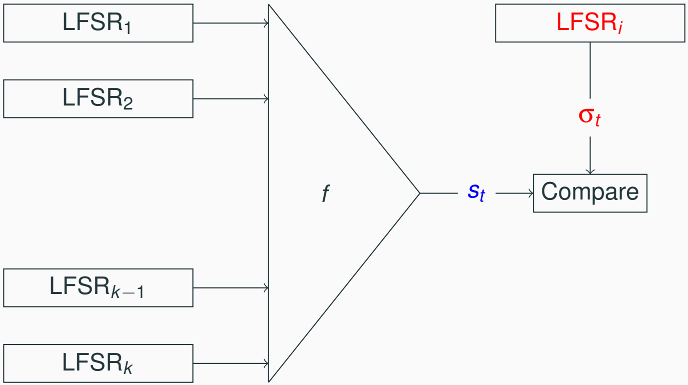
The monomial equivalence does not affect the complexity of algebraic attacks [Gong et al. 11]

Univariate correlation attacks

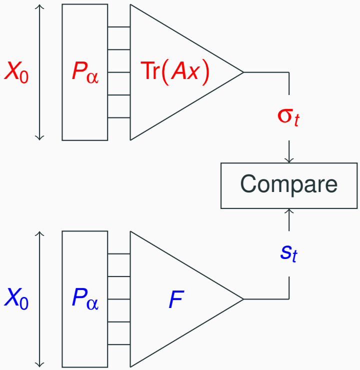
Correlation attack [Siegenthaler 85]



Criterion

The criterion besides the correlation attack is the **resiliency**.

Fast correlation attack [Meier - Staffelbach 88]

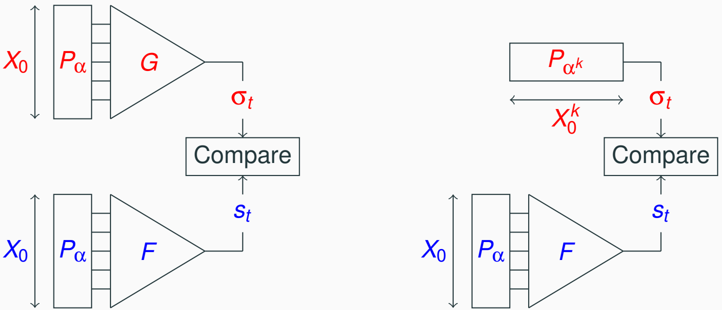


Criterion

The criterion besides the fast correlation attack is the **non-linearity**.

Generalized fast correlation attacks

$G(x) = \mathrm{Tr}(Ax^k)$



Generalized non-linearity [Gong & Youssef 01]

Relevant security criterion:

Generalized non-linearity

$$\mathrm{GNL}(f) = d(f, \{\mathrm{Tr}(\lambda x^k, \lambda \in \mathbb{F}_{2^n}, \gcd(k, 2^n - 1) = 1\})$$

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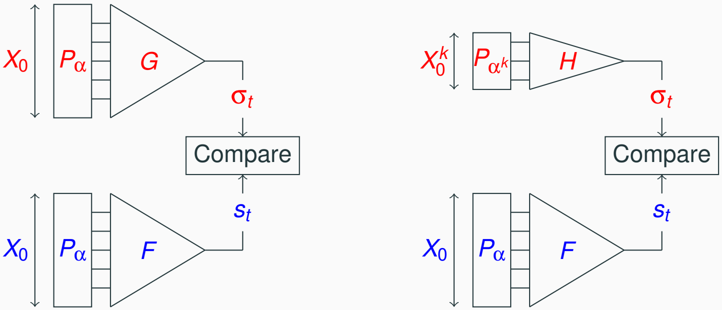
And if k is not coprime to $2^n - 1$?

A more efficient correlation attack

When $\gcd(k, 2^n - 1) > 1$ and F correlated to $G(X) = H(X^k)$.



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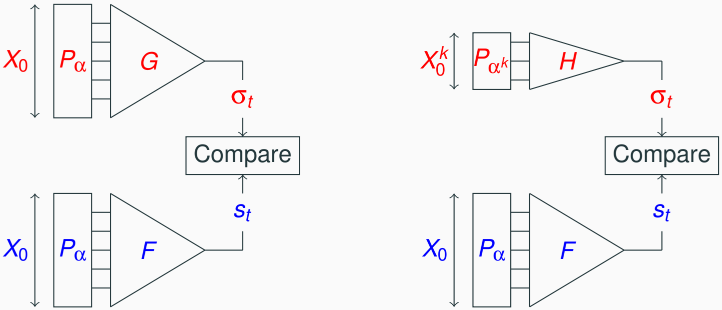

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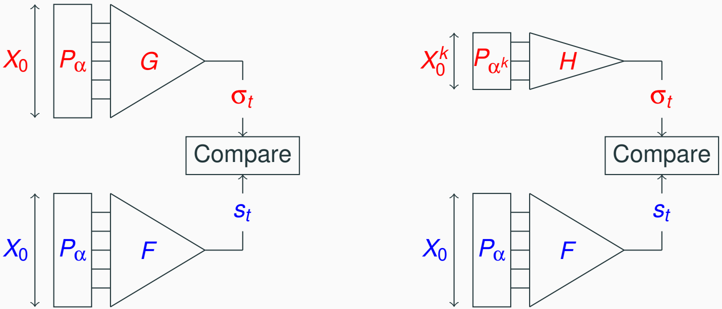

- Number of states of the small generator: $\tau_k = \mathrm{ord}(\alpha^k)$.
- Exhaustive search on X_0^k: Time $= \frac{\tau_k \log(\tau_k)}{\varepsilon^2}$

Recovering the remaining bits of the initial state

Property

We get $\log_2(\tau_k)$ bits of information on X_0 where $\tau_k = \mathrm{ord}(\alpha^k)$:

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Property

We get $\log_2(\tau_k)$ bits of information on X_0 where $\tau_k = \mathrm{ord}(\alpha^k)$:

If we perform two distinct correlation attacks with k_1 et k_2, then we get $\log_2(\mathrm{lcm}(\tau_{k_1}, \tau_{k_2}))$ bits of information.

First improvement

The complexity

$$\text{Time} = \frac{\tau_k \log(\tau_k)}{\varepsilon^2}$$

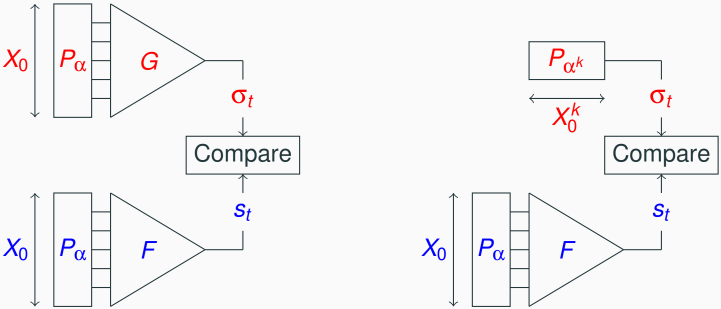
can be reduced to

$$\text{Time} = \tau_k \log \tau_k + \frac{2 \log(\tau_k)}{\varepsilon^2} \ .$$

with a fast Fourier transform [Canteaut - Naya-Plasencia 2012]

Second improvement

$G(X) = H(X^k)$ when H is linear:



- Size of the small LFSR: $L(k) = \mathrm{ord}(2) \mod \tau_k$.
- If $L(k) < n$ and H is linear $\longrightarrow$ fast correlation attack.

What we really do

- Split the state on the multiplicative subgroups
- recover independantly the information
- gather information

Impact on Boolean functions

New criterion

Definition (Multiplicative subgroup resiliency ?)

Let F be a Boolean function with n variables, let k dividing $2^n - 1$, and τ the multiplicative order of α^k and $d = \gcd(k, \tau)$, we say that F is k - MS resilient if and only if

$$\max_{G(x)=H(x^k)} \varepsilon(F(x), G(x)) = \frac{\tau}{d} 2^{-n}$$

Question

Is it possible to reach the value of τ/d for every possible τ ?

When H is linear

Question

What is the value of

$$\min_{f} \max_{G(x)=\mathrm{Tr}(\lambda x^k)} \varepsilon(F(x), G(x))$$

Conclusions

Conclusion and open questions

Conclusion

- Generalized criterion for f besides the generalized non-linearity.
- The attack does not apply when $(2^n - 1)$ is prime.

Open questions

- Find good filtering Boolean functions ?
- Compute efficiently a good approximation of the filtering function ?

Thank You for your attention !

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Questions ?