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Recent algebraic attacks on the McEliece cryptosystem

J.-P. Tillich (Inria de Paris)

June 21, 2023

Joint work

- ▶ “On the dimension and structure of the square of the dual of a Goppa code”, R. Mora, J.-P. Tillich, *Designs, Codes and Cryptography*, 2022
- ▶ “Polynomial time key-recovery attack on high rate random alternant codes”, M. Bardet, R. Mora, J.-P. Tillich, <https://arxiv.org/abs/2304.14757>
- ▶ “A new approach based on quadratic forms to attack the McEliece cryptosystem”, A. Couvreur, R. Mora, J.-P. Tillich, <https://eprint.iacr.org/2023/950>

1. The McEliece cryptosystem

- ▶ 1978 McEliece cryptosystem based on Goppa codes.
- Secret Key : The algebraic structure of an $[n, k]_q$ Goppa code \mathcal{C} which has an efficient decoding algorithm for decoding t errors
- Public Key : an arbitrary generator matrix G of \mathcal{C} .
- Encryption : $m \in \mathbb{F}_q^k \longmapsto y \stackrel{\text{def}}{=} mG + e$ with $|e| = t$.
- Decryption : $y \longmapsto m = \text{Decode}(y)$.

Advantages/drawbacks

Advantages

- Post Quantum, 4th-round finalist of the NIST competition;
- 55 years of research have not changed much the picture

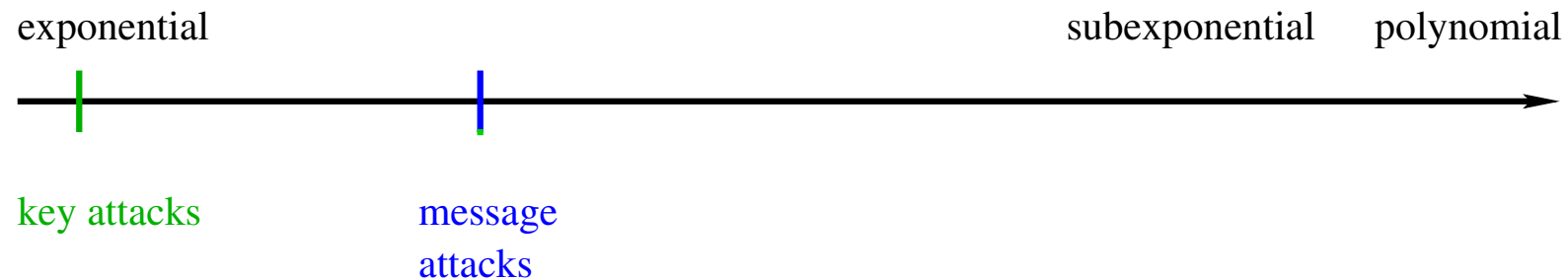
Compl. of key attacks \gg Compl. of message attacks $\approx 2^{\alpha n}$
with $\alpha \approx \text{Constant}$

- Efficient encryption and decryption

Drawbacks

- Huge size of the keys, Classic McEliece \approx 260 Kbytes.

Key Attacks/Message Attacks (pre 2011)



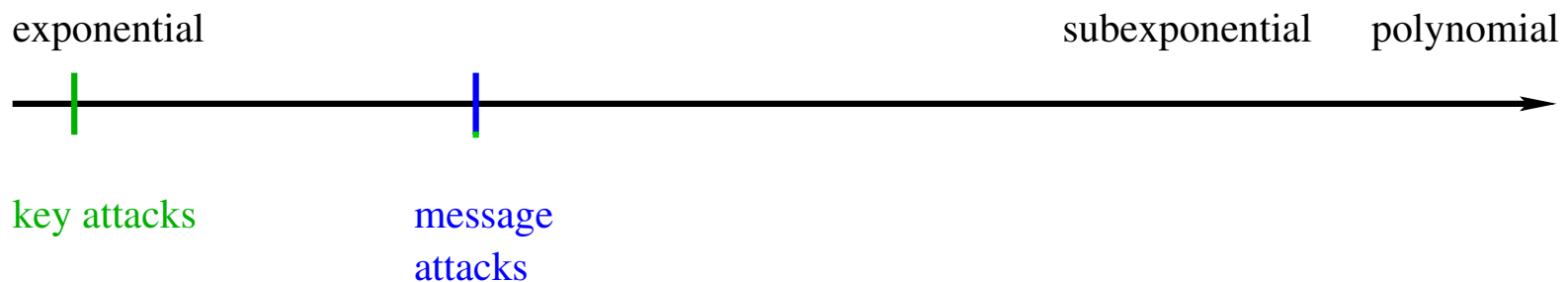
- ▶ **Key attack:** (pre 2011) Enumerating all Goppa polynomial + solving the code-equivalence problem
- ▶ **Message attack:** Decoding a generic linear code

Key Attacks/Message Attacks (2011)

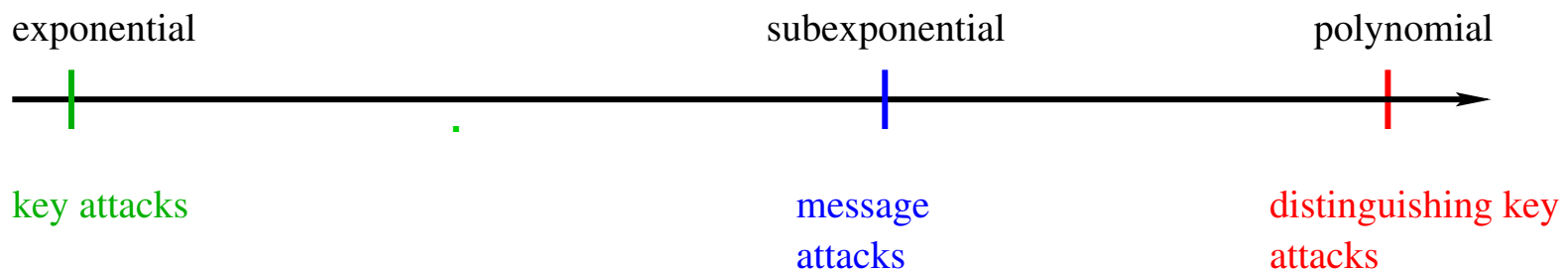
► Distinguishing Attack

[Faugère-Gauthier-Otmani-Perret-Tillich-2011]: distinguishing a Goppa/alternant code from a generic linear code

► $n - k = \Theta(n)$



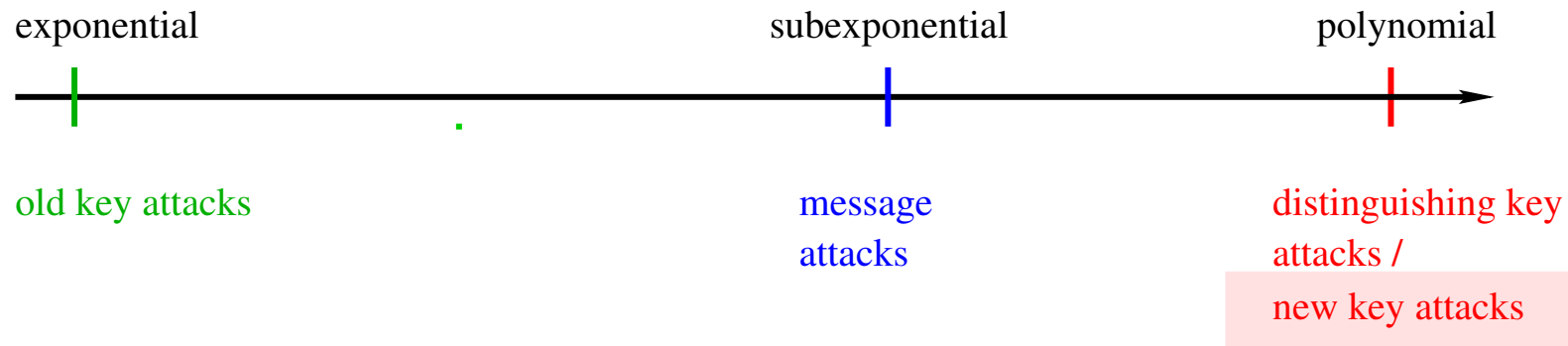
► $n - k = O(n^{\frac{1}{2}})$



Key Attacks/Message Attacks [BMT23]

Assumptions:

1. the code should be **distinguishable** ($\Rightarrow n - k = O\left(n^{\frac{1}{2}}\right)$) with the method of [FGOPT11]
2. should be a **generic alternant** code rather than a Goppa code
3. $q \in \{2, 3\}$



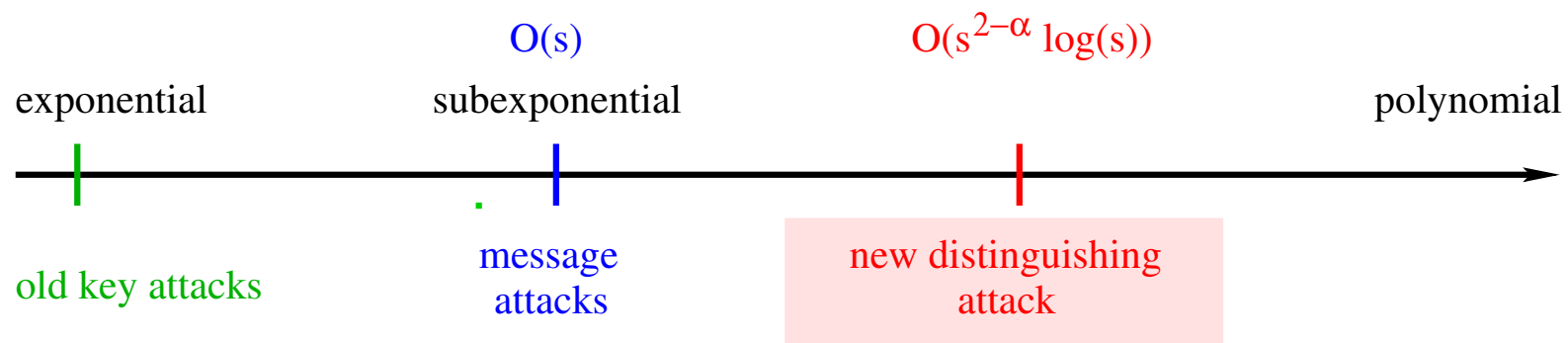
A new approach and a new distinguisher [CMT23]

- ▶ Associating a space of quadratic forms to an alternant/Goppa code and looking for low rank quadratic forms in it by Gröbner basis techniques
 \Rightarrow a new distinguisher in characteristic 2

$$s \stackrel{\text{def}}{=} n - k$$

$$n = s^\alpha$$

$$\alpha \in (1, 2)$$



2. Alternant and Goppa Codes

Generalized Reed-Solomon codes

Definition 1. [Generalized Reed-Solomon code] k and n integers with $1 \leq k < n \leq q$ where q is a power of a prime number. The generalized Reed-Solomon code $\mathbf{GRS}_k(\mathbf{x}, \mathbf{y})$ of dimension k associated to a pair $(\mathbf{x}, \mathbf{y}) \in \mathbb{F}_q^n \times \mathbb{F}_q^n$ where \mathbf{x} is an n -tuple of distinct elements of \mathbb{F}_q and the entries y_i are arbitrary nonzero elements in \mathbb{F}_q is defined as:

$$\mathbf{GRS}_k(\mathbf{x}, \mathbf{y}) \stackrel{\text{def}}{=} \left\{ (y_1 p(x_1), \dots, y_n p(x_n)) : p \in \mathbb{F}_q[X], \deg p < k \right\}.$$

\mathbf{x} is the *support* and \mathbf{y} the *multiplier*.

[Sidelnikov-Shestakov1992]: recover from an arbitrary generator matrix of a GRS code \mathcal{C} , a tuple (\mathbf{x}, \mathbf{y}) such that $\mathcal{C} = \mathbf{GRS}(\mathbf{x}, \mathbf{y})$ (all what is needed to decode \mathcal{C} efficiently).

Alternant codes

Definition 1. [alternant/Goppa code] $\mathbf{x} \in \mathbb{F}_{q^m}^n, \mathbf{y} \in \mathbb{F}_{q^m}^n$ as in def. of GRS codes, $\Gamma \in \mathbb{F}_{q^m}[z]$, $\deg \Gamma = r$. The *alternant* code $\mathbf{Alt}_r(\mathbf{x}, \mathbf{y})$, resp. *Goppa* code $\mathbf{Gop}(\mathbf{x}, \Gamma)$ of support \mathbf{x} , degree r and extension degree m are defined by

$$\begin{aligned} \mathbf{Alt}_r(\mathbf{x}, \mathbf{y}) &\stackrel{\text{def}}{=} \mathbf{GRS}_r(\mathbf{x}, \mathbf{y})^\perp \cap \mathbb{F}_q^n \\ &= \mathbf{GRS}_{n-r}(\mathbf{x}, \mathbf{y}^\perp) \cap \mathbb{F}_q^n \quad (\text{subfield subcode of GRS}) \end{aligned}$$

$$\mathbf{Gop}(\mathbf{x}, \Gamma) = \mathbf{Alt}_r\left(\mathbf{x}, \frac{1}{\Gamma(\mathbf{x})}\right)$$

$$\begin{aligned} \mathbf{GRS}_r(\mathbf{x}, \mathbf{y})^\perp &= \mathbf{GRS}_{n-r}(\mathbf{x}, \mathbf{y}^\perp) \\ \mathbf{y}^\perp &\stackrel{\text{def}}{=} \left(\frac{1}{y_i \pi'_x(x_1)}, \dots, \frac{1}{y_i \pi'_x(x_1)} \right) \\ \pi_x(\mathbf{x}) &\stackrel{\text{def}}{=} (x - x_1) \cdots (x - x_n) \end{aligned}$$

3. The square code

- ▶ **Key ingredient** for the [FGOPT11]/[MT22] distinguisher and the [BMT23] attack
- ▶ Introduced for cryptanalyzing the Berger-Loidreau scheme by **Wieschebrink** in 2010

The square code

Definition 2. [Componentwise product] Given two vectors $\mathbf{a} = (a_1, \dots, a_n)$ and $\mathbf{b} = (b_1, \dots, b_n) \in \mathbb{F}_q^n$, we denote by $\mathbf{a} \star \mathbf{b}$ the componentwise product

$$\mathbf{a} \star \mathbf{b} \stackrel{\text{def}}{=} (a_1 b_1, \dots, a_n b_n)$$

Definition 3. [Product of codes & square code] The *star product code* denoted by $\mathcal{A} \star \mathcal{B}$ of \mathcal{A} and \mathcal{B} is the vector space *spanned by all products* $\mathbf{a} \star \mathbf{b}$ where \mathbf{a} and \mathbf{b} range over \mathcal{A} and \mathcal{B} respectively. When $\mathcal{B} = \mathcal{A}$, $\mathcal{A} \star \mathcal{A}$ is called the *square code* of \mathcal{A} and is rather denoted by \mathcal{A}^2 .

Dimension of the square code

\mathcal{A} and \mathcal{B} codes with respective bases (\mathbf{a}_i) and (\mathbf{b}_j) .

1. $\dim(\mathcal{A} \star \mathcal{B}) \leq \dim(\mathcal{A}) \dim(\mathcal{B})$ (generated by the $\mathbf{a}_i \star \mathbf{b}_j$'s)

2. $\dim(\mathcal{A}^2) \leq \binom{\dim(\mathcal{A}) + 1}{2}$ (generated by the $\mathbf{a}_i \star \mathbf{a}_j$'s with $i \leq j$)

What is wrong with generalized Reed-Solomon codes ?

When \mathcal{C} is a **random** code of length n , with high probability

$$\dim(\mathcal{C}^2) = \min \left\{ \binom{\dim(\mathcal{C}) + 1}{2}, n \right\}$$

When \mathcal{C} is a **generalized Reed-Solomon** code

$$\dim(\mathcal{C}^2) = \min \{2 \dim(\mathcal{C}) - 1, n\}$$

The explanation

$$\mathbf{c} = (y_1 p(x_1), \dots, y_n p(x_n)), \mathbf{c}' = (y_1 q(x_1), \dots, y_n q(x_n)) \in \mathbf{GRS}_k(\mathbf{x}, \mathbf{y})$$

where p and q are two polynomials of degree at most $k - 1$.

$$\mathbf{c} \star \mathbf{c}' = (y_1^2 p(x_1) q(x_1), \dots, y_n^2 p(x_n) q(x_n)) = (y_1^2 r(x_1), \dots, y_n^2 r(x_n))$$

where r is a polynomial of degree $\leq 2k - 2$.

$$\implies \mathbf{c} \star \mathbf{c}' \in \mathbf{GRS}_{2k-1}(\mathbf{x}, \mathbf{y}^2)$$

What happens for alternant/Goppa codes [FGOPT11][MT22]?

Alternant/Goppa code \mathcal{C} over \mathbb{F}_q of length n , degree r , ext. deg. m

$$\dim \mathcal{C}^\perp \stackrel{\text{typ.}}{=} rm$$

$$\dim \left((\mathcal{C}_{\text{Gop}}^\perp)^2 \right) \leq \dim \left((\mathcal{C}_{\text{alt}}^\perp)^2 \right)$$

$$\dim \left((\mathcal{C}^\perp)^2 \right) \leq \min \left(n, \underbrace{\binom{mr+1}{2}}_{\dim \mathcal{R}^2} - \Omega(mr^2 \log r) \right)$$

$\mathcal{R} \stackrel{\text{def}}{=} \text{random code of length } n, \dim rm$

4. [BMT23] : filtration attack + Gröbner bases



- ▶ Transforming the distinguisher into an attack

A theorem

\mathcal{C} a code of length n , $I, J \subset \{1, \dots, n\}$

$$\mathbf{x}_J = (x_j)_{j \in J}$$

$$\mathbf{x}_{\setminus I} = (x_j)_{j \notin I}$$

$$\text{Shortened code } \mathbf{Sh}_I(\mathcal{C}) = \{\mathbf{c}_{\setminus I} : \mathbf{c} \in \mathcal{C}, c_i = 0, \forall i \in I\}$$

Theorem 1. [BMT23] Let $\mathbf{Alt}_r(\mathbf{x}, \mathbf{y})$ be an alternant code on \mathbb{F}_q such that $r \geq q + 1$ and let $\mathcal{C} \stackrel{\text{def}}{=} \mathbf{Alt}_r(\mathbf{x}_{\setminus i}, \mathbf{y}_{\setminus i})^\perp$, $\mathcal{D} \stackrel{\text{def}}{=} (\mathbf{Sh}_i(\mathbf{Alt}_r(\mathbf{x}, \mathbf{y})^\perp))^2$, then

$$\mathcal{C} \star \mathbf{Alt}_{r-1}(\mathbf{x}_{\setminus i}, \mathbf{y}_{\setminus i}(\mathbf{x}_{\setminus i} - x_i))^\perp \subseteq \mathcal{D}$$

Filtration

- For given subspaces \mathcal{A} and \mathcal{B} , computing the largest subspace \mathcal{X} such that

$$\mathcal{A} \star \mathcal{X} \subseteq \mathcal{B}$$

is just solving a linear system.

Conjecture 1. For $r \geq q + 1$ and if $(\text{Sh}_i(\mathbf{Alt}_r(\mathbf{x}, \mathbf{y})^\perp))^2$ is not the full space. Let \mathcal{X} be largest subspace such that $\mathcal{C} \star \mathcal{X} \subset \mathcal{D}$. Then for a generic alternant code

$$\mathcal{X} = \mathbf{Alt}_{r-1}(\mathbf{x}_{\setminus i}, \mathbf{y}_{\setminus i}(\mathbf{x}_{\setminus i} - x_i))^\perp$$

For a Goppa code $\mathbf{Alt}_{r-1}(\mathbf{x}_{\setminus i}, \mathbf{y}_{\setminus i}(\mathbf{x}_{\setminus i} - x_i))^\perp \subset \mathcal{X}$

Filtration (ii)+attack

- ▶ $\mathbf{Alt}_r(\mathbf{x}, \mathbf{y}) \rightarrow \mathbf{Alt}_{r-1}(\mathbf{x}_{\setminus i}, \dots)^\perp \rightarrow \dots \rightarrow \mathbf{Alt}_q(\mathbf{x}_{\setminus I}, \dots)^\perp$
- ▶ The support \mathbf{x} and multiplier \mathbf{y} of an alternant code $\mathbf{Alt}_r(\mathbf{x}, \mathbf{y})$ can be recovered **efficiently** by a suitable algebraic modeling + Gröbner bases techniques when $r = 3 \Rightarrow$

efficient attack when $q \in \{2, 3\}$

GRS codes

$$\mathcal{C} \stackrel{\text{def}}{=} \mathbf{GRS}_k(\mathbf{x}_{\setminus i}, \mathbf{y}_{\setminus i})$$

$$= \{(y_j P(x_j))_{j \neq i} : \deg P \leq k - 1\}$$

$$\mathcal{D} \stackrel{\text{def}}{=} (\mathbf{Sh}_i(\mathbf{GRS}_k(\mathbf{x}, \mathbf{y})))^2$$

$$= \{(y_j (x_j - x_i)^2 P(x_j))_{j \neq i} : \deg P \leq 2k - 4\} \text{ since}$$

$$\mathbf{Sh}_i(\mathbf{GRS}_k(\mathbf{x}, \mathbf{y})) = \{(y_j (x_j - x_i) P(x_j))_{j \neq i} : \deg P \leq k - 2\}$$

$$\mathcal{X} = \mathbf{GRS}_{k-2}(\mathbf{x}_{\setminus i}, \mathbf{y}_{\setminus i}(\mathbf{x}_{\setminus i} - x_i)^2)$$

$$= \{(y_j (x_j - x_i)^2 P(x_j))_{j \neq i} : \deg P \leq k - 3\}$$

$$\mathcal{C} \star \mathcal{X} = \mathcal{D}$$

5. A new tool : quadratic forms

Going to the big field

$\mathcal{C} \subseteq (\mathbb{F}_q)^n$, $\mathcal{C}_{\mathbb{F}_{q^m}} \stackrel{\text{def}}{=} \text{linear span of } \mathcal{C} \text{ over } \mathbb{F}_{q^m}$.

Proposition 1.

$$\left(\mathbf{Alt}_r(\mathbf{x}, \mathbf{y})^\perp\right)_{\mathbb{F}_{q^m}} = \sum_{j=0}^{m-1} \mathbf{GRS}_r(\mathbf{x}, \mathbf{y})^{(q^j)} = \sum_{j=0}^{m-1} \mathbf{GRS}_r(\mathbf{x}^{q^j}, \mathbf{y}^{q^j})$$

$$\mathbf{c}_a \stackrel{\text{def}}{=} \mathbf{y}\mathbf{x}^a \in \left(\mathbf{Alt}_r(\mathbf{x}, \mathbf{y})^\perp\right)_{\mathbb{F}_{q^m}}$$

$$\mathbf{c}_0 \star \mathbf{c}_2 = \mathbf{c}_1^2$$

Quadratic relations between codewords

\mathcal{C} an $[n, k]$ -code over \mathbb{F} , $\mathcal{V} = \{\mathbf{v}_1, \dots, \mathbf{v}_k\}$ a basis of \mathcal{C}

$$\mathcal{C}_{\text{rel}}(\mathcal{V}) \stackrel{\text{def}}{=} \left\{ \mathbf{c} = (c_{i,j})_{1 \leq i \leq j \leq k} \mid \sum_{i \leq j} c_{i,j} \mathbf{v}_i \star \mathbf{v}_j = 0 \right\} \subseteq \mathbb{F}^{\binom{k+1}{2}}$$

$$Q_{\mathbf{c}}(x_1, \dots, x_k) = \sum_{i \leq j} c_{i,j} x_i x_j$$

$$\mathbf{x} \mathbf{M}_{\mathbf{c}} \mathbf{y}^{\top} = Q_{\mathbf{c}}(\mathbf{x} + \mathbf{y}) - Q_{\mathbf{c}}(\mathbf{x}) - Q_{\mathbf{c}}(\mathbf{y})$$

$$\mathcal{C}_{\text{mat}}(\mathcal{V}) \stackrel{\text{def}}{=} \left\{ \mathbf{M}_{\mathbf{c}} = (m_{i,j})_{\substack{1 \leq i \leq k \\ 1 \leq j \leq k}} \mid \mathbf{c} = (c_{i,j})_{1 \leq i \leq j \leq k} \in \mathcal{C}_{\text{rel}}(\mathcal{V}) \right\}$$

$$\mathbf{M}_{\mathbf{c}} \stackrel{\text{def}}{=} \begin{cases} m_{i,j} \stackrel{\text{def}}{=} m_{j,i} \stackrel{\text{def}}{=} c_{i,j}, & 1 \leq i < j \leq k, \\ m_{i,i} \stackrel{\text{def}}{=} 2c_{i,i}, & 1 \leq i \leq k. \end{cases}$$

Low rank matrices

$$\mathbf{c}_0 \star \mathbf{c}_2 = \mathbf{c}_1^2 \Rightarrow$$

odd characteristic

characteristic 2

$$M_{\mathbf{c}} = \begin{pmatrix} 0 & 0 & 1 & 0 & \cdots & 0 \\ 0 & -2 & 0 & \vdots & \ddots & \vdots \\ 1 & 0 & 0 & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & 0 & \cdots & 0 \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & 0 & \cdots & 0 \end{pmatrix} \quad \begin{pmatrix} 0 & 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 0 & \vdots & \ddots & \vdots \\ 1 & 0 & 0 & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & 0 & \cdots & 0 \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & 0 & \cdots & 0 \end{pmatrix}$$

rank = 3 rank = 2

basis **invariant**, since \exists an invertible matrix \mathbf{P} such that

$$\mathcal{C}_{\text{mat}}(\mathcal{A}) = \mathbf{P} \mathcal{C}_{\text{mat}}(\mathcal{B}) \mathbf{P}^{\top}$$

MinRank Problem

Problem 1. [odd characteristic] Let M_1, \dots, M_K be K *symmetric* matrices in $\mathbb{F}^{N \times N}$, find an $M \in \langle M_1, \dots, M_K \rangle_{\mathbb{F}}$ of rank 3.

Problem 2. [characteristic 2] Let M_1, \dots, M_K be K *skew-symmetric* matrices in $\mathbb{F}^{N \times N}$, find an $M \in \langle M_1, \dots, M_K \rangle_{\mathbb{F}}$ of rank 2.

- ▶ Geometric argument on matrix codes \Rightarrow probability that there are rank 2 (char 2) or rank 3 matrix in a random matrix code of the same dimension(s) as $\mathcal{C}_{\text{mat}}(\mathcal{V})$ when $\text{rate}(\mathcal{C}) \leq 1/3$ is $o(1)$.

Algebraic modeling in characteristic 2

- \mathcal{C} an $[n, k]$ code,
- $\mathcal{C}_{\text{mat}}(\mathcal{V}) \in \mathbb{F}^{k \times k}$ the associated skew-symmetric matrix code
 $\dim \mathcal{C}_{\text{mat}}(\mathcal{V}) = \binom{k}{2} - (n - k)$ when \mathcal{C} is not [FGOPT11]-distinguishable.
- skew-symmetric $\mathbf{M} = (m_{ij})_{\substack{1 \leq i \leq k \\ 1 \leq j \leq k}} \in \mathbb{F}^{k \times k}$

$\text{rank}(\mathbf{M}) \leq 2 \Rightarrow$ all principal minors of \mathbf{M} of size 4 are 0

$$\Rightarrow m_{ab}m_{cd} + m_{ac}m_{bd} + m_{ad}m_{bc} = 0, \forall a, b, c, d$$

$\mathbf{M} \in \mathcal{C}_{\text{mat}}(\mathcal{V}) \rightarrow n - k$ linear equations

Hilbert Series

- **Homogeneous** ideal $\mathcal{I} \in \mathbb{K}[\mathbf{z}]$, $\mathbf{z} = (z_1, \dots, z_n)$,
- **Hilbert function** of the ring $R = \mathbb{K}[\mathbf{z}]/\mathcal{I}$ defined as

$$\text{HF}_R(d) \stackrel{\text{def}}{=} \dim_{\mathbb{K}}(\mathbb{K}[\mathbf{z}]_d) - \dim_{\mathbb{K}}(\mathcal{I}_d)$$

$$\mathbb{K}[\mathbf{z}]_d \stackrel{\text{def}}{=} \{f \in \mathbb{K}[\mathbf{z}] \mid \deg(f) = d\}$$

$$\mathcal{I}_d \stackrel{\text{def}}{=} \mathcal{I} \cap \mathbb{K}[\mathbf{z}]_d$$

Can be computed in time $\approx n^{\omega d}$

Generic linear code/Goppa or alternant code

- ▶ alternant/Goppa case: $\text{HF}(d) > 0$ for all d .
- ▶ generic linear $[n, k]$ -code:

$$\begin{aligned} \text{HF}(d) &= \max\left(0, \sum_{i=0}^d (-1)^i \binom{s}{i} \text{HF}(d-i)\right) \\ &= \max\left(0, \sum_{i=0}^d (-1)^i \binom{s}{i} \left(\binom{k+d-i-2}{d-i}^2 - \binom{k+d-i-2}{d-i-1} \right)\right) \end{aligned}$$

where $s \stackrel{\text{def}}{=} n - k$.

$$d_0 \stackrel{\text{def}}{=} \min\{d : \text{HF}(d) = 0\} \sim c \frac{k^2}{n-k}$$

Generalization of the distinguisher

► $HF(1) = \text{old distinguisher} : HF(1) = \binom{k+1}{2} - \dim \mathcal{C}^2$

$HF(2)$	$256 \geq n \geq 77$	$n = 76$	$n = 75$	$n = 74$	$n = 73$
Random code	0	10	71	133	196
Alternant code	20	20	71	133	196
Goppa code	80	80	80	133	196

Table 1: $HF(2)$ for random, alternant and Goppa codes with $q = 4, m = 4, r = 4$. In bold = distinguishable lengths.

6. New attack in the (old) distinguishable regime

Assumption 1. The parameters are in the *old distinguishable regime* and $r < q + 1$ (alternant) or $r < q - 1$ (Goppa).

► Recall that

$$\left(\mathbf{Alt}_r(\mathbf{x}, \mathbf{y})^\perp\right)_{\mathbb{F}_{q^m}} = \sum_{j=0}^{m-1} \mathbf{GRS}_r(\mathbf{x}, \mathbf{y})^{(q^j)} = \sum_{j=0}^{m-1} \mathbf{GRS}_r(\mathbf{x}^{q^j}, \mathbf{y}^{q^j})$$

⇒ Basis \mathcal{A} of $\left(\mathbf{Alt}_r(\mathbf{x}, \mathbf{y})^\perp\right)_{\mathbb{F}_{q^m}}$ of the form

$$\mathcal{A} = (\mathbf{a}_0, \dots, \mathbf{a}_{r-1}, \mathbf{a}_0^q, \dots, \mathbf{a}_{r-1}^q, \dots, \mathbf{a}_0^{q^{m-1}}, \dots, \mathbf{a}_{r-1}^{q^{m-1}}),$$

$$\mathbf{a}_i \stackrel{\text{def}}{=} \mathbf{y}\mathbf{x}^i$$

► From [MT22] the quadratic relations are generated by

$$\mathbf{a}_a^{q^l} \star \mathbf{a}_b^{q^l} - \mathbf{a}_c^{q^l} \star \mathbf{a}_d^{q^l} \text{ for } a + b = c + d.$$

The Crucial Observation

The elements \mathbf{A} of $\mathcal{C}_{\text{mat}}(\mathcal{A})$ are of the form (blocks of size r)

$$\mathbf{A} = \begin{bmatrix} \mathbf{A}_0 & 0 & \cdots & 0 \\ 0 & \mathbf{A}_2 & & \\ \vdots & & \ddots & 0 \\ 0 & \cdots & 0 & \mathbf{A}_{m-1} \end{bmatrix},$$

If $\text{rank}(\mathbf{A}) = rm - 1 \Rightarrow \exists j : \text{rank}(\mathbf{A}_j) = r - 1, \text{rank}(\mathbf{A}_i) = r, i \neq j$

if $\mathbf{v} \in \ker(\mathbf{A}) \Rightarrow \mathbf{v} = (\mathbf{0}_r, \dots, \mathbf{0}_r, \mathbf{v}_j, \mathbf{0}_r, \dots, \mathbf{0}_r)$

\Rightarrow identify the vectors generating a single GRS code $\mathbf{GRS}_r(x^{q^j}, y^{q^j})$

Conclusion/Open Problems

- ▶ Finding a distinguisher in odd characteristic
- ▶ Turning the distinguisher into an attack
- ▶ Attacking Goppa codes in the whole distinguishable regime
- ▶ A general methodology for studying the security of the McEliece cryptosystem