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POLYNOMIALS OVER $\mathbb{Q}$ SOLVING AN EMBEDDING PROBLEM

par Núria VILA

In 1980 we have constructed infinitely many polynomials with coefficients in $\mathbb{Q}$ having absolute Galois group the alternating group A_n (cf. [2]). Recently, J.-P. Serre (cf. [4]) has described the obstruction to a certain embedding problem as the Hasse-Witt invariant of an associated quadratic form.

In this note, using Serre's result, we see that the fields defined by the equations of [2], Th. 2.1, can be embedded in a Galois extension with Galois group $\hat{A}_n$, the representation group of A_n , if and only if $n \equiv 0 \pmod{8}$ or $n \equiv 2 \pmod{8}$ and n sum of two squares. Then, for these values of n , every central extension of A_n occurs as Galois group over $\mathbb{Q}$.

I would like to thank Professor J.-P. Serre for communicating to me the results of [2] and for pointing out to me the case $n \equiv 0 \pmod{8}$.

Let K be a number field and R its ring of integers. Let

$$F(X) = X^n + aX^2 + bX + c, \quad ac \neq 0,$$

be a polynomial of $R[X]$ satisfying the following conditions:

(i) $F(X)$ is irreducible and primitive.

(ii) $b^2(n-1)^2 = 4acn(n-2)$.

(iii) $(-1)^{n/2}c$ is a square.

(iv) If $u = -b(n-1)/2(n-2)a$, there exists a prime ideal $\mathfrak{p}$ of R such that

$$c(n-1) \notin \mathfrak{p}, \quad f(u) \in \mathfrak{p} \quad \text{and} \quad 3 \nmid v_{\mathfrak{p}}(f(u)).$$

In [2], Th. 1.1, we have proved that if n is an even integer, $n > 2$, the Galois group of $F(X)$ over K is isomorphic to the alternating group A_n .

Key-words : Algebraic Number theory - Field theory and polynomials - Inverse problem of Galois theorem.

The main result of this note is

THEOREM. — Suppose that n is an even integer, $n > 6$. Let N be the splitting field of the polynomial $F(X)$. The extension N/K can be embedded in a Galois extension with Galois group a given central extension of A_n if and only if

$$\begin{array}{ll} n \equiv 0 \pmod{8}, & \text{or} \\ n \equiv 2 \pmod{8} & \text{and } n \text{ is a sum of two squares.} \end{array}$$

Since for n even, we have constructed infinitely many polynomials with coefficients in $\mathbb{Q}$ satisfying the condition (i), (ii), (iii), (iv) (cf. [2], Th. 2.1), we have :

COROLLARY. — Every central extension of A_n appears as Galois group over $\mathbb{Q}$ if

$$\begin{array}{ll} n \equiv 0 \pmod{8}, & \text{or} \\ n \equiv 2 \pmod{8} & \text{and } n \text{ is a sum of two squares.} \end{array}$$

Other values of n are considered in [5].

First of all, we prove the following

LEMMA. — Let $f(X) = X^n + aX^2 + bX + c \in \mathbb{R}[X]$ be an irreducible polynomial such that $b^2(n-1)^2 = 4acn(n-2)$. Let $E = K(\theta)$, where θ is a root of $f(X)$. The quadratic form $\text{Tr}_{E/K}(X^2)$ diagonalizes as follows :

$$\text{Tr}_{E/K}(X^2) \sim \begin{cases} nX_1^2 - (n-2)aX_2^2 + X_3X_4 + \cdots + X_{n-1}X_n, & \text{if } n \text{ is even,} \\ nX_1^2 + X_2X_3 + \cdots + X_{n-1}X_n, & \text{if } n \text{ is odd.} \end{cases}$$

Proof. — Easy computations give :

$$\begin{array}{ll} \text{Tr}(1) = n, & \text{Tr}(\theta^i) = 0, \quad 1 \leq i \leq n-3, \\ \text{Tr}(\theta^{n-2}) = -(n-2)a, & \text{Tr}(\theta^{n-1}) = -(n-1)b. \end{array}$$

Suppose that n is even; let $m = n/2$. Clearly $1, \theta, \dots, \theta^{m-1}$ are pairwise orthogonal vectors of E and $\theta, \dots, \theta^{m-2}$ are isotropic vectors of E . Then the quadratic space E splits :

$$E \sim \langle 1 \rangle \perp \langle \theta^{m-1} \rangle \perp (m-2)H \perp E',$$

where H is a hyperbolic plane and E' is a quadratic plane.

Since $b^2(n-1)^2 = 4ac(n-2)$, the polynomial

$$g(X) = nf(X) - Xf'(X)$$

has a double root u . Hence the discriminant of $f(X)$ is

$$\begin{aligned} d &= (-1)^{n(n-1)/2} R(f, f') \\ &= (-1)^{n(n-1)/2} R(g, f')/n \\ &= (-1)^{n(n-1)/2} (n-2)^{n-1} b^{n-1} f'(u)^2/n, \end{aligned}$$

where $R(f, f')$ is the resultant of f and f' .

Consequently, the discriminant of E' in K^*/K^{*2} is -1 . Thus, E' is a hyperbolic plane.

The proof in the case n odd runs in an analogous way.

Proof of the Theorem. — Let $\hat{A}_n$ be the representation group (*Darstellungsgruppe*) of A_n (cf. [1]). The group $\hat{A}_n$ is the only non-trivial extension of A_n with kernel $\mathbb{Z}/2$ (cf. [3]).

Let $0 \neq a_n \in H^2(A_n, \mathbb{Z}/2)$ be the cohomological class associated to $\hat{A}_n$. It is easy to see (cf. [5], Th. 1.1) that our embedding problem is reduced to embed N/K in a Galois extension with Galois group $\hat{A}_n$. As it is well-known, the obstruction to this embedding problem is $\inf(a_n)$, where

$$\inf: H^2(A_n, \mathbb{Z}/2) \rightarrow H^2(G_K, \mathbb{Z}/2)$$

is the homomorphism associated to the epimorphism $p: G_K \rightarrow A_n$. Let θ be a root of $F(X)$ and $L = \mathbb{Q}(\theta)$. By [4], Th. 1,

$$\inf(a_n) = w(L/K),$$

where $w(L/K)$ denote the Hasse-Witt invariant of the quadratic form $\text{Tr}_{L/K}(X^2)$. By the Lemma, we have

$$w(L/K) = (n, (-1)^{n/2}) \otimes (-1, (-1)^{n(n-2)/8}).$$

Therefore, $w(L/K) = 1$ if and only if $n \equiv 0 \pmod{8}$, or $n \equiv 2 \pmod{8}$ and n is a sum of two squares.

Remark. — If n is an odd square and $f(X) \in \mathbb{R}[X]$ is a polynomial satisfying the conditions (i), (ii) and (iv), the Galois group of $f(X)$ is also isomorphic to A_n (cf. [2], Th. 1.6). Then, we can proceed as in the

Theorem to prove that, in this case, the splitting field of $f(X)$ can be embedded in a Galois extension with Galois group any central extension of A_n .

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