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ON A CONJECTURE OF LENNY JONES ABOUT CERTAIN MONOGENIC POLYNOMIALS

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Abstract

Let $K = \mathbb{Q}(\theta)$ be an algebraic number field with θ satisfying a monic irreducible polynomial $f(x)$ of degree n over $\mathbb{Q}$. The polynomial $f(x)$ is said to be monogenic if $\{1, \theta, \ldots, \theta^{n-1}\}$ is an integral basis of K. Deciding whether or not a monic irreducible polynomial is monogenic is an important problem in algebraic number theory. In an attempt to answer this problem for a certain family of polynomials, Jones ['A brief note on some infinite families of monogenic polynomials', *Bull. Aust. Math. Soc.* **100** (2019), 239–244] conjectured that if $n \geq 3$, $1 \leq m \leq n-1$, $\gcd(n, mB) = 1$ and A is a prime number, then the polynomial $x^n + A(Bx+1)^m \in \mathbb{Z}[x]$ is monogenic if and only if $n^n + (-1)^{n+m}B^n(n-m)^{n-m}m^mA$ is square-free. We prove that this conjecture is true.

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1. Introduction and statements of results

Let $K = \mathbb{Q}(\theta)$ be an algebraic number field and let $f(x)$ of degree n be the minimal polynomial of θ over $\mathbb{Q}$. The polynomial $f(x)$ is said to be monogenic if $\{1, \theta, \ldots, \theta^{n-1}\}$ is an integral basis of K.

Denote the ring of algebraic integers of K by $\mathbb{Z}_K$. The field K is said to be monogenic if there exists $\alpha \in \mathbb{Z}_K$ such that $\mathbb{Z}_K = \mathbb{Z}[\alpha]$. It is well known that if $f(x)$ is monogenic, then the number field K is monogenic but the converse is not always true (for example, $\mathbb{Q}(\sqrt{d})$, where $d \neq 1$ is a square-free integer congruent to 1 modulo 4).

The discriminant of a monic polynomial over a field $\mathbb{F}$ of degree n having roots $\theta_1, \ldots, \theta_n$ in the algebraic closure of $\mathbb{F}$ is $\Delta_f = \prod_{1\leq i<j\leq n}(\theta_i - \theta_j)^2$. It is a classical result in algebraic number theory that if $f(x)$ is the minimal polynomial of an algebraic integer θ over $\mathbb{Q}$, then the discriminant Δ_f of $f(x)$ and the discriminant d_K of $K = \mathbb{Q}(\theta)$ are related by the formula

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$$\Delta_f = [\mathbb{Z}_K : \mathbb{Z}[\theta]]^2 d_K. \tag{1.1}$$

Clearly if Δ_f is square-free, then $f(x)$ is monogenic but the converse need not be true. Jones [4, 6] constructed infinite families of monogenic polynomials having non square-free discriminant. In [7], Jones showed that there exist infinitely many primes $p \geq 3$ and integers $t \geq 1$ coprime to p, such that $f(x) = x^p - 2ptx^{p-1} + p^2t^2x^{p-2} + 1$ is nonmonogenic and, in [5], he gave infinite families of monogenic polynomials using a new discriminant formula.

Throughout the paper, $f(x) = x^n + A(Bx + 1)^m \in \mathbb{Z}[x]$ is an irreducible polynomial with $n \geq 3$ and $1 \leq m \leq n-1$, θ is a root of f, $K = \mathbb{Q}(\theta)$ is the corresponding algebraic number field, Δ_f denotes the discriminant of $f(x)$ and $\operatorname{Ind}_K(\theta)$ denotes the group index $[\mathbb{Z}_K : \mathbb{Z}[\theta]]$. From [4, Theorem 3.1],

$$\Delta_f = (-1)^{n(n-1)/2} A^{n-1} [n^n + (-1)^{n+m} B^n (n-m)^{n-m} m^m A]. \tag{1.2}$$

THEOREM 1.1. *Let A, B, n, m be integers with $1 \leq m \leq n-1, n > 2$ and $B \neq 0$. Assume that $\gcd(n, mB) = 1$. Then an irreducible polynomial of the type $f(x) = x^n + A(Bx + 1)^m$ is monogenic if and only if both A and $n^n + (-1)^{n+m} B^n (n-m)^{n-m} m^m A$ are square-free.*

REMARK 1.2. In Theorem 1.1, the assumption that $\gcd(n, mB) = 1$ cannot be dropped. For example, consider the polynomial $f(x) = x^3 - 6(3x + 1)$. Here $n = 3, m = 1, A = -6$ and $B = 3$. Note that $f(x)$ is irreducible over $\mathbb{Q}$. The polynomial $f(x)$ is monogenic and has discriminant $\Delta_f = 23.2^2.3^5$. However, $n^n + (-1)^{n+m} B^n (n-m)^{n-m} m^m A = 23.3^3$ is not square-free.

The following corollary is an immediate consequence of Theorem 1.1. It is conjectured by Jones in [4, Conjecture 4.1].

COROLLARY 1.3. *Let p be a prime number, and n, m and B be positive integers with $1 \leq m \leq n-1,\ n > 2$ and $\gcd(n, mB) = 1$. Then $f(x) = x^n + p(Bx + 1)^m$ is monogenic if and only if $n^n + (-1)^{n+m} B^n (n-m)^{n-m} m^m p$ is square-free.*

EXAMPLE 1.4. Let p be an odd prime number and let a, b be positive integers with $n > 2$. Consider the polynomial $f(x) = x^n + ax^2 + bx + p$ with $b^2 = 4ap$. Note that $f(x)$ satisfies Eisenstein's criterion with respect to p, so it is irreducible over $\mathbb{Q}$. The polynomial $x^n + ax^2 + bx + p$ with $b^2 = 4ap$ can be reduced to the form $x^n + p(Bx + 1)^2$ with $B = b/2p$. If $\gcd(n, 2B) = 1$, that is, $\gcd(n, b/p) = 1$, then Corollary 1.3 implies that $f(x)$ is monogenic if and only if $n^n + (-1)^n 4(b/2p)^n (n-2)^{n-2} p$ is square-free.

EXAMPLE 1.5. Let B be an integer not divisible by 3 with $|B| \geq 4$ and let $A \neq \pm 1$ be a nonzero square-free integer. Then the polynomial $f(x) = x^3 + A(Bx + 1)^2$ is irreducible by Perron's criterion, which states that if $f(x) = x^n + a_{n-1}x^{n-1} + \cdots + a_1 x + a_0 \in \mathbb{Z}[x]$ with $a_0 \neq 0$ and $|a_{n-1}| > 1 + |a_{n-2}| + \cdots + |a_0|$, then the polynomial $f(x)$ is irreducible over $\mathbb{Q}$. In view of Theorem 1.1, the polynomial $x^3 + A(Bx + 1)^2$ is monogenic if and only if $4AB^3 - 27$ is square-free.

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2. Preliminary results

In what follows, for a prime number p and a given polynomial $g(x) \in \mathbb{Z}[x]$, $\overline{g}(x)$ will denote the polynomial obtained by reducing each coefficient of $g(x)$ modulo p.

Let $f(x) \in \mathbb{Z}[x]$ be a monic irreducible polynomial having a root θ and let $L = \mathbb{Q}(\theta)$ be an algebraic number field. In 1878, Dedekind proved the following criterion which gives a necessary and sufficient condition to be satisfied by $f(x)$ so that p does not divide $\mathrm{Ind}_L(\theta)$.

THEOREM 2.1 (Dedekind's criterion, [2]; see also [1, Theorem 6.1.4]). *Let $L = \mathbb{Q}(\theta)$ be an algebraic number field and $f(x)$ the minimal polynomial of the algebraic integer θ over $\mathbb{Q}$. Let p be a prime and $\overline{f}(x) = \overline{g}_1(x)^{e_1} \cdots \overline{g}_t(x)^{e_t}$ be the factorisation of $\overline{f}(x)$ as a product of powers of distinct irreducible polynomials over $\mathbb{Z}/p\mathbb{Z}$, with each $g_i(x) \in \mathbb{Z}[x]$ monic. Let $M(x) = (f(x) - g_1(x)^{e_1} \cdots g_t(x)^{e_t})/p \in \mathbb{Z}[x]$. Then p does not divide $\mathrm{Ind}_L(\theta)$ if and only if, for each i, either $e_i = 1$ or $\overline{g}_i(x)$ does not divide $\overline{M}(x)$.*

With the notation as in Theorem 2.1, one can easily check that if $f(x)$ is monogenic, then for each prime p dividing Δ_f, either $e_i = 1$ or $\overline{g}_i(x)$ does not divide $\overline{M}(x)$ for each i.

DEFINITION 2.2. A polynomial $a_n x^n + a_{n-1}x^{n-1} + \cdots + a_0$ in $\mathbb{Z}[x]$ with $a_n \neq 0$ is called an Eisenstein polynomial with respect to a prime p if $p \nmid a_n$, $p \mid a_i$ for $0 \leq i \leq n-1$ and $p^2 \nmid a_0$.

The following result is known as Eisenstein's criterion (see [3]). It will be used in the proof of Corollary 1.3.

THEOREM 2.3. *Let $g(x) = a_n x^n + a_{n-1}x^{n-1} + \cdots + a_0 \in \mathbb{Z}[x]$ with $n \geq 1$. If there is a prime number p such that $p \nmid a_n, p \mid a_{n-1}, \ldots, p \mid a_0$ and $p^2 \nmid a_0$, then $g(x)$ is irreducible over $\mathbb{Q}$.*

The following lemma will be used in the proof of Theorem 1.1.

LEMMA 2.4 [8, Lemma 2.17]. *Let α be an algebraic integer and let $L = \mathbb{Q}(\alpha)$. If the minimal polynomial of α over $\mathbb{Q}$ is an Eisenstein polynomial with respect to the prime p, then $\mathrm{Ind}_L(\alpha)$ is not divisible by p.*

3. Proof of Theorem 1.1 and Corollary 1.3

PROOF OF THEOREM 1.1. Clearly $A \neq 0$. Suppose that θ is a root of $f(x)$ and $K = \mathbb{Q}(\theta)$. From (1.2),

$$\Delta_f = (-1)^{n(n-1)/2} A^{n-1}[n^n + (-1)^{n+m} B^n (n-m)^{n-m} m^m A].$$

First suppose that the polynomial $f(x)$ is monogenic. Then $\mathrm{Ind}_K(\theta) = 1$. Let p be a prime dividing Δ_f. The following cases arise.

Case 1: $p \mid A$. Then $f(x) \equiv x^n \bmod p$ and $M(x) = A(Bx+1)^m/p$. As $n \geq 3$, by Dedekind's criterion, we see that $\overline{x}$ should not divide $\overline{M}(x)$. This implies that $p^2 \nmid A$. Thus, A is square-free. Suppose that p^2 divides $(n^n + (-1)^{n+m} B^n (n-m)^{n-m} m^m A)$.

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Then the hypothesis $p \mid A$ implies that $p \mid n$. Since $n \geq 3$ and A is square-free, we have $p \mid B^n(n-m)^{n-m}m^m$, that is, $p \mid m(n-m)B$, which is not true because $\gcd(n, mB) = 1$. It follows that p^2 cannot divide $(n^n + (-1)^{n+m}B^n(n-m)^{n-m}m^mA)$ and so $(n^n + (-1)^{n+m}B^n(n-m)^{n-m}m^mA)$ is square-free.

Case 2: $p \nmid A$. Then p will divide $(n^n + (-1)^{n+m}B^n(n-m)^{n-m}m^mA)$. Keeping in mind the hypothesis $\gcd(n, mB) = 1$, it is easy to see that $p \nmid n$ and so $p \nmid Bm(n-m)$. Let α be a repeated root of $\overline{f}(x) = x^n + \overline{A}(\overline{B}x + 1)^m$ in the algebraic closure of $\mathbb{Z}/p\mathbb{Z}$. Then

$$\alpha^n + A(B\alpha + 1)^m \equiv 0 \bmod p$$

and

$$n\alpha^{n-1} + mAB(B\alpha + 1)^{m-1} \equiv 0 \bmod p.$$

So $n\alpha^{n-1} \equiv -mAB(B\alpha + 1)^{m-1} \bmod p$. By substitution,

$$-\alpha mAB(B\alpha + 1)^{m-1} + nA(B\alpha + 1)^m \equiv 0 \bmod p,$$

that is,

$$(B\alpha + 1)^{m-1}(\alpha AB(n-m) + nA) \equiv 0 \bmod p.$$

If $B\alpha + 1 \equiv 0 \bmod p$, then $\alpha \equiv -1/B \bmod p$, which yields the contradiction $(-1)^n/\overline{B}^n = \overline{f}(-1//\overline{B}) = \overline{f}(\overline{\alpha}) = 0$. Thus, $\alpha AB(n-m) + nA \equiv 0 \bmod p$, so that

$$\alpha \equiv -\frac{nA}{AB(n-m)} \bmod p \tag{3.1}$$

is the unique repeated root of $\overline{f}(x)$ in $\mathbb{Z}/p\mathbb{Z}$ and it is easy to show that α has multiplicity 2. So, assuming that α is a positive integer satisfying (3.1), we can write

$$\begin{aligned} f(x) &= (x - \alpha + \alpha)^n + A(B(x - \alpha + \alpha) + 1)^m, \\ &= \sum_{k=0}^{n} \binom{n}{k} \alpha^{n-k}(x-\alpha)^k + A\bigg(\sum_{k=0}^{m} \binom{m}{k} (B\alpha + 1)^{m-k} B^k (x-\alpha)^k\bigg), \\ &= (x-\alpha)^2 h(x) + f'(\alpha)(x-\alpha) + f(\alpha), \end{aligned}$$

where $f'(x)$ is the derivative of $f(x)$ and

$$h(x) = \sum_{k=2}^{n} \binom{n}{k} \alpha^{n-k}(x-\alpha)^{k-2} + A\bigg(\sum_{k=2}^{m} \binom{m}{k} (B\alpha + 1)^{m-k} B^k (x-\alpha)^{k-2}\bigg)$$

is in $\mathbb{Z}[x]$. Then $\overline{f}(x) = (x - \overline{\alpha})^2\overline{h}(x)$, where $\overline{h}(x) \in \mathbb{Z}[x]$ is separable. Let $\prod_{i=1}^{t} \overline{h}_i(x)$ be the factorisation of $\overline{h}(x)$ into a product of distinct irreducible polynomials $\overline{h}_i(x) \in \mathbb{Z}/p\mathbb{Z}[x]$ with each $h_i(x) \in \mathbb{Z}[x]$ monic. Then we can write

$$f(x) = (x-\alpha)^2\bigg(\prod_{i=1}^{t} h_i(x) + pg(x)\bigg) + f'(\alpha)(x-\alpha) + f(\alpha),$$

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for some polynomial $g(x) \in \mathbb{Z}[x]$. This implies that

$$M(x) = \frac{1}{p}[p(x-\alpha)^2 g(x) + (x-\alpha)f'(\alpha) + f(\alpha)].$$

In view of Dedekind's criterion and the hypothesis that $f(x)$ is monogenic, we see that $f(\alpha) \not\equiv 0 \bmod p^2$. Equivalently,

$$(n^n + (-1)^{n+m}(n-m)^{n-m}m^m B^n A) \not\equiv 0 \bmod p^2.$$

Hence, $(n^n + (-1)^{n+m}(n-m)^{n-m}m^m B^n A)$ is square-free.

Conversely, suppose A and $(n^n + (-1)^{n+m}(n-m)^{n-m}m^m B^n A)$ are square-free. If $A = \pm 1$, then using (1.1), we see that $\mathrm{Ind}_K(\theta) = 1$, that is, $f(x)$ is monogenic. If p be a prime divisor of A, then $f(x)$ is an Eisenstein polynomial with respect to the prime p. Therefore, by Lemma 2.4, $p \nmid \mathrm{Ind}_K(\theta)$. Hence, by (1.1), $f(x)$ is monogenic. This completes the proof of the theorem. □

PROOF OF COROLLARY 1.3. It is easy to verify that $f(x)$ satisfies Eisenstein's criterion with respect to the prime p. So $f(x)$ is an irreducible polynomial. Hence, the result follows from Theorem 1.1. □

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