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The Galois theory of the lemniscate

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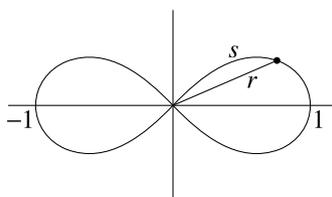
ABSTRACT

This article studies the Galois groups that arise from division points of the lemniscate. We compute these Galois groups two ways: first, by class field theory, and second, by proving the irreducibility of lemnatomic polynomials, which are analogs of cyclotomic polynomials. We also discuss Abel's theorem on the lemniscate and explain how lemnatomic polynomials relate to Chebyshev polynomials.

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1. Introduction

The lemniscate is the curve defined by the polar equation $r^2 = \cos(2\theta)$:



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In the first quadrant, the arc length s is related to the radial distance r by the elliptic integral

$$s = \int_0^r \frac{dt}{\sqrt{1-t^4}}. \tag{1}$$

The arc length of the first-quadrant portion is $\int_0^1 \frac{dt}{\sqrt{1-t^4}}$, denoted by $\varpi/2$ in analogy with $\pi/2 = \int_0^1 \frac{dt}{\sqrt{1-t^2}}$. Following Abel, the inverse function of (1) is denoted $\varphi(s) = r$. The goal of this paper is to compute the Galois group

$$\text{Gal}\left(K\left(\varphi\left(\frac{2\varpi}{n}\right)\right)/K\right), \tag{2}$$

where $K = \mathbb{Q}(i)$ and n is a positive odd integer. Geometrically, $\varphi(\frac{2\varpi}{n})$ tells us how to find the first n -division point of the lemniscate, and the size of the Galois group (2) determines whether or not we can divide the lemniscate into n pieces by ruler and compass. This will lead to a quick proof of Abel’s theorem on the lemniscate, which characterizes those n ’s for which this can be done (see Section 5 for a precise statement).

Our main result is an isomorphism

$$\text{Gal}\left(K\left(\varphi\left(\frac{2\varpi}{n}\right)\right)/K\right) \simeq (\mathbb{Z}[i]/n\mathbb{Z}[i])^\times \tag{3}$$

when $n > 0$ is odd. We will prove this two ways, first using class field theory and complex multiplication in the spirit of [9], and second using *lemnatomic polynomials*, which are analogs of cyclotomic polynomials. The key step will be to prove that lemnatomic polynomials are irreducible.

Here is a brief summary of the paper. Section 2 explains how $\varphi(s)$ extends to an elliptic function $\varphi(z)$ and describes the period lattice L and associated elliptic curve E . We also recall how complex multiplication by $\mathbb{Z}[i]$ gives explicit formulas for $\varphi(\beta z)$ when $\beta \in \mathbb{Z}[i]$. Section 3 introduces the field $K_\beta = K(\varphi(\frac{2\varpi}{\beta}))$ for $\beta \in \mathbb{Z}[i]$ relatively prime to $1+i$ (we say that β is *odd*) and constructs an injection

$$\text{Gal}(K_\beta/K) \hookrightarrow (\mathbb{Z}[i]/\beta\mathbb{Z}[i])^\times. \tag{4}$$

We also give some alternate descriptions of K_β that clarify its relation to the elliptic curve E . We conclude by identifying K_β as the ray class field of K for the modulus $2(1+i)\beta$ when $\beta \in \mathbb{Z}[i]$ is odd and use class field theory and complex multiplication to prove that (4) is an isomorphism. Section 4 defines the lemnatomic polynomial Λ_β and proves its irreducibility over K by an elementary argument, leading to an elementary proof of (3). We also determine the degree and constant term of Λ_β . Section 5 shows how Abel’s theorem on the lemniscate follows from the irreducibility of lemnatomic

polynomials, and the final Section 6 explores a surprisingly strong analogy between lemnatomic polynomials and irreducible factors of Chebyshev polynomials.

2. The complex lemniscatic function

As explained in [3, Chapter 15], the function $\varphi(s)$ from the Introduction extends to a function of period 2ϖ on \mathbb{R} and satisfies the addition law

$$\varphi(x + y) = \frac{\varphi(x)\varphi'(y) + \varphi(y)\varphi'(x)}{1 + \varphi(x)^2\varphi(y)^2} \tag{5}$$

and the differential equation

$$\varphi'(s)^2 = 1 - \varphi(s)^4. \tag{6}$$

As is well known, we extend φ to a meromorphic function on \mathbb{C} via

$$\varphi(z) = \varphi(x + iy) = \frac{\varphi(x)\varphi'(y) + i\varphi(y)\varphi'(x)}{1 - \varphi(x)^2\varphi(y)^2}.$$

By [3, Section 15.3], φ is an elliptic function for the lattice

$$L = \mathbb{Z}(1 + i)\varpi + \mathbb{Z}(1 - i)\varpi \tag{7}$$

whose zeros (all simple) are at points $\equiv 0, \varpi \pmod L$ and whose poles (also simple) are at points $\equiv (1 \pm i)\varpi/2 \pmod L$. Also, φ is an odd function and

$$\varphi(z) = \varphi(w) \iff z = (-1)^{m+n}w + (m + in)\varpi, \quad m, n \in \mathbb{Z}. \tag{8}$$

For the rest of the paper, we will use the notation

$$K = \mathbb{Q}(i), \quad \mathcal{O} = \mathbb{Z}[i].$$

In the introduction we defined $\beta \in \mathcal{O}$ to be odd if it is relatively prime to $1 + i$. Note that

$$\begin{aligned} \beta \in \mathcal{O} \text{ is odd} &\iff \beta = m + in, \quad m, n \in \mathbb{Z}, \quad m + n \text{ odd} \\ &\iff \beta \equiv i^\varepsilon \pmod{2(1 + i)} \text{ for some } \varepsilon \in \{0, 1, 2, 3\}. \end{aligned}$$

We say that $\beta \in \mathcal{O}$ is *even* if it is not odd, i.e., if $1 + i$ divides β .

If $\beta \in \mathcal{O}$ is nonzero and L is the period lattice (7), then note that

$$\frac{1}{\beta}L/L \simeq \mathcal{O}/\beta\mathcal{O}$$

as \mathcal{O} -modules. We say that $\delta \in \frac{1}{\beta}L$ is a β -torsion generator if $[\delta] \in \frac{1}{\beta}L/L$ generates $\frac{1}{\beta}L/L$ as an \mathcal{O} -module. Any two β -torsion generators δ, δ' satisfy $\delta \equiv \alpha\delta' \pmod L$ for some $[\alpha] \in (\mathcal{O}/\beta\mathcal{O})^\times$. We will use the β -torsion generator $\delta_\beta = \frac{(1+i)\varpi}{\beta}$ frequently.

The elliptic function φ also has complex multiplication by \mathcal{O} .

Theorem 2.1. *Let $\beta \in \mathcal{O}$ be odd. Then there exist coprime polynomials $P_\beta(x), Q_\beta(x) \in \mathcal{O}[x]$ and $\varepsilon \in \{0, 1, 2, 3\}$ such that*

1. For all $z \in \mathbb{C}$, $\varphi(\beta z) = M_\beta(\varphi(z))$, where

$$M_\beta(x) = i^\varepsilon x \frac{P_\beta(x^4)}{Q_\beta(x^4)}.$$

2. $\beta \equiv i^\varepsilon \pmod{2(1+i)}$.
3. $P_\beta(x)$ and $Q_\beta(x)$ have degree $(N(\beta) - 1)/4$, where $N(\beta) = \beta\bar{\beta}$ is the norm of β .
4. The β -division polynomial $xP_\beta(x^4)$ has $N(\beta)$ distinct roots given by $\varphi(\alpha\delta)$ for $[\alpha] \in \mathcal{O}/\beta\mathcal{O}$ and $\delta \in \frac{1}{\beta}L$ a fixed β -torsion generator.
5. $P_\beta(x)$ is monic and $Q_\beta(x) = x^{(N(\beta)-1)/4} P_\beta(1/x)$.
6. Suppose π is an odd prime in \mathcal{O} and let $d = (N(\pi) - 1)/4$. Then

$$P_\pi(x) = x^d + a_1x^{d-1} + \cdots + a_d,$$

such that each a_j is divisible by π and $a_d = i^{-\varepsilon}\pi$.

Proof. See [3, Theorem 15.4.8] for (1), (2), (3), (5) and (6). Note that (6) is due to Eisenstein. As for part (4), let $\delta_\beta = \frac{(1+i)\varpi}{\beta}$. For any $\alpha \in \mathcal{O}$, $\varphi(\alpha\delta_\beta)$ is a root of $xP_\beta(x^4)$ since φ vanishes at $\beta\alpha\delta_\beta \in L$. Now suppose that $\alpha, \alpha' \in \mathcal{O}$ satisfy $\varphi(\alpha\delta_\beta) = \varphi(\alpha'\delta_\beta)$. By (8), we have

$$\alpha\delta_\beta = (-1)^{m+n}\alpha'\delta_\beta + (m+in)\varpi, \quad m, n \in \mathbb{Z}.$$

This implies $\alpha(1+i) = (-1)^{m+n}\alpha'(1+i) + (m+in)\beta$, so that $m+in$ is even. It follows easily that $\alpha \equiv \alpha' \pmod \beta$. Thus $xP_\beta(x^4)$ has at least $N(\beta) = |\mathcal{O}/\beta\mathcal{O}|$ distinct roots, namely $\varphi(\alpha\delta_\beta)$ for $[\alpha] \in \mathcal{O}/\beta\mathcal{O}$. Since this polynomial has degree $N(\beta)$, these are all of its roots. Then the same holds for any other β -torsion generator δ since $\delta \equiv \alpha\delta_\beta \pmod L$ for some $[\alpha] \in (\mathcal{O}/\beta\mathcal{O})^\times$. \square

We conclude this section with a few words about the elliptic curve $E = \mathbb{C}/L$ associated to the period lattice $L = \mathbb{Z}(1+i)\varpi + \mathbb{Z}(1-i)\varpi$ from (7).

Lemma 2.2. *The Weierstrass equation of E is $Y^2 = 4X^3 + X$.*

Proof. The Weierstrass equation of $E = \mathbb{C}/L$ is $Y^2 = 4X^3 - g_2(L)X - g_3(L)$, and $g_3(L) = 0$ since E has complex multiplication by $\mathcal{O} = \mathbb{Z}[i]$. As for $g_2(L)$, we know from [9] that the lattice $L' = \mathbb{Z}2\varpi + \mathbb{Z}2\varpi i$ has $g_2(L') = \frac{1}{4}$. Since $L' = (1+i)L$, we obtain

$$\frac{1}{4} = g_2(L') = g_2((1+i)L) = (1+i)^{-4}g_2(L) = -\frac{1}{4}g_2(L). \quad \square$$

Let $\wp(z) = \wp(z; L)$ be the Weierstrass \wp -function for L . The elliptic functions φ and φ' have period lattice L and hence are rational functions of \wp and \wp' . By analyzing the behavior at zeros and poles, one can show that

$$\varphi(z) = -2\frac{\wp(z)}{\wp'(z)}, \quad \varphi'(z) = \frac{4\wp(z)^2 - 1}{4\wp(z)^2 + 1}. \quad (9)$$

Note that by (6), φ and φ' parametrize the curve

$$y^2 = 1 - x^4, \quad (10)$$

while \wp and \wp' parametrize the curve of Lemma 2.2. Then (9) tells us that the curves of Lemma 2.2 and (10) are related by the birational transformation

$$x = -2\frac{X}{Y}, \quad y = \frac{4X^2 - 1}{4X^2 + 1}.$$

3. Preliminary analysis of the Galois group

We begin with the field $K_\beta = K(\wp(\frac{2\varpi}{\beta}))$ defined in the Introduction.

Proposition 3.1. *If $\beta \in \mathcal{O}$ is odd and δ is any β -torsion generator, then*

$$K_\beta = K(\varphi(\delta)) = K(\varphi(\delta), \varphi'(\delta)) = K(\wp(\delta), \wp'(\delta)) = K(E[\beta]),$$

where $K(E[\beta])$ is the field obtained from K by adjoining the coordinates of the β -torsion points of E .

Proof. We first show that $\frac{2\varpi}{\beta}$ is a β -torsion generator. Since β is odd, we have $u\beta + v(1-i) = 1$ for some $u, v \in \mathcal{O}$. Multiplying this by $\delta_\beta = \frac{(1+i)\varpi}{\beta}$ gives $v\frac{2\varpi}{\beta} \equiv \delta_\beta \pmod{L}$, and our claim follows.

Let δ, δ' be β -torsion generators. As noted above, $\delta \equiv \alpha\delta' \pmod{L}$ for some $[\alpha] \in (\mathcal{O}/\beta\mathcal{O})^\times$, where we may assume that α is odd since β is (if α is even, replace it with $\alpha + \beta$.) Then $\varphi(\delta) = \varphi(\alpha\delta')$ and the latter is in $K(\varphi(\delta'))$ by part (1) of Theorem 2.1. This implies $K(\varphi(\delta)) = K(\varphi(\delta'))$, and then $K_\beta = K(\varphi(\delta))$ follows using $\delta' = \frac{2\varpi}{\beta}$.

For the second equality of the proposition, we use (5) to obtain

$$\varphi\left(\frac{2\varpi}{\beta}\right) = \varphi\left(\frac{(1-i)(1+i)\varpi}{\beta}\right) = \varphi((1-i)\delta_\beta) = \frac{(1-i)\varphi(\delta_\beta)\varphi'(\delta_\beta)}{1 + \varphi(\delta_\beta)^4}.$$

This implies $\varphi'(\delta_\beta) \in K(\varphi(\frac{2\varpi}{\beta}), \varphi(\delta_\beta)) = K(\varphi(\delta_\beta))$, which shows that the second equality holds for δ_β . Then the addition laws for φ and φ' show that it also holds for any β -torsion generator δ .

The third equality follows since (9) is birational, and the final equality follows since $(\wp(\delta), \wp'(\delta)) \in E[\beta]$ generates $E[\beta]$ as an \mathcal{O} -module. \square

Proposition 3.1 shows that K_β is a Galois extension of K (this also follows from Theorem 2.1). We compute the Galois group of K_β/K as follows.

Proposition 3.2. *Let $\beta \in \mathcal{O}$ be odd. Then for any $\sigma \in \text{Gal}(K_\beta/K)$, there is a unique $[\alpha] \in (\mathcal{O}/\beta\mathcal{O})^\times$ such that $\sigma(\varphi(\delta)) = \varphi(\alpha\delta)$ for any β -torsion generator δ . Furthermore, the map $\sigma \mapsto [\alpha]$ defines an isomorphism*

$$\text{Gal}(K_\beta/K) \simeq (\mathcal{O}/\beta\mathcal{O})^\times.$$

Proof. For later purposes, we separate the argument into two parts. First, the elementary methods used in [3, Theorem 15.5.1] give an injection

$$\text{Gal}(K_\beta/K) \hookrightarrow (\mathcal{O}/\beta\mathcal{O})^\times. \tag{11}$$

We prove surjectivity using class field theory, similar to what Rosen does in [9]. By [13, Theorem 5.6], the ray class field of K for the modulus $2(1+i)\beta$ is

$$L = K(\wp(\delta_{2(1+i)\beta})^2).$$

Since \mathcal{O} is a PID with $\mathcal{O}^\times = \{\pm 1, \pm i\}$ and β is odd, the Artin map and the Chinese Remainder Theorem give isomorphisms

$$\text{Gal}(L/K) \simeq (\mathcal{O}/2(1+i)\beta\mathcal{O})^\times / \mathcal{O}^\times \simeq (\mathcal{O}/\beta\mathcal{O})^\times.$$

Using (9), we also have

$$L = K(\varphi'(\delta_{2(1+i)\beta})) = K\left(\varphi'\left(\frac{\varpi}{2\beta}\right)\right).$$

Differentiating the addition law for $\varphi(z - \frac{\varpi}{2})$ gives the identity

$$\varphi'\left(z - \frac{\varpi}{2}\right) = 2\frac{\varphi(z)}{1 + \varphi(z)^2}. \tag{12}$$

Since β is odd, there exists $\gamma \in \mathcal{O}$ such that $2(1+i)\gamma - \beta = i^\varepsilon$. Then $\gamma\delta_\beta - \frac{\varpi}{2} = i^\varepsilon \frac{\varpi}{2\beta}$. Using $\varphi'(iz) = \varphi'(z)$ and (12), we obtain

$$\varphi'\left(\frac{\varpi}{2\beta}\right) = \varphi'\left(i^\varepsilon \frac{\varpi}{2\beta}\right) = \varphi'\left(\gamma\delta_\beta - \frac{\varpi}{2}\right) = 2 \frac{\varphi(\gamma\delta_\beta)}{1 + \varphi(\gamma\delta_\beta)^2} \in K(\varphi(\delta_\beta)) = K_\beta.$$

Thus $K \subseteq L \subseteq K_\beta$, so that $|\text{Gal}(K_\beta/K)| \geq |\text{Gal}(L/K)| = |(\mathcal{O}/\beta\mathcal{O})^\times|$. Since (11) is an injection, we see that $L = K_\beta$ and (11) is an isomorphism. \square

In Section 4 we use elementary methods to prove that the map (11) is an isomorphism.

In 1980, Rosen [9] applied class field theory to the lemniscate, though his approach was slightly different. He used the lattice $L' = \mathbb{Z}2\varpi + \mathbb{Z}2\varpi i$, which corresponds to the elliptic curve $E' = \mathbb{C}/L'$ defined by $Y^2 = 4X^3 - \frac{1}{4}X$. In order to prove Abel's theorem on the lemniscate (see Theorem 5.1 below), he used the isomorphism

$$\text{Gal}\left(K\left(\wp\left(\frac{2\varpi}{n}; L'\right)^2\right)/K\right) \simeq (\mathcal{O}/n\mathcal{O})^\times / \mathcal{O}^\times$$

since $K(\wp(\frac{2\varpi}{n}; L')^2)$ is the ray class field of K for the modulus n . The first person to apply class field theory to the lemniscate was Takagi in his 1903 thesis, where he showed that all abelian extensions of $K = \mathbb{Q}(i)$ are generated by division values of the lemniscatic elliptic function (see Schappacher [10, p. 259] for precise references).

Proposition 3.2 for the case when β is an odd prime power was first proved by Lennormeyer in [6, Theorem 8.19].

4. Lemnatomic polynomials

In this section we present an elementary proof of our main result. Pursuing the analogy between the roots of unity and the division points of the lemniscate leads to an algebraic theory for the lemniscate akin to the circle's cyclotomy. We introduce the *lemnatomic polynomials* and prove their irreducibility over K . Our main result (3) follows as a corollary.

Definition 4.1. Let $\beta \in \mathcal{O}$ be odd and set $\delta_\beta = \frac{(1+i)\varpi}{\beta}$. We call

$$\Lambda_\beta(x) = \prod_{[\alpha] \in (\mathcal{O}/\beta\mathcal{O})^\times} (x - \varphi(\alpha\delta_\beta))$$

the β^{th} *lemnatomic polynomial*.

In this definition, we can replace δ_β with any β -torsion generator δ . Furthermore, the roots of Λ_β are $\varphi(\delta)$ as δ ranges over all lattice-inequivalent β -torsion generators.

Note also that $\Lambda_\beta = \Lambda_{\beta'}$ when β and β' are associates in \mathcal{O} since Λ_β depends only on the ideal generated by β . It will often be convenient to specify an associate. Recall that an odd $\beta \in \mathcal{O}$ satisfies $\beta \equiv i^\varepsilon \pmod{2(1+i)}$ for $\varepsilon \in \{0, 1, 2, 3\}$.

Definition 4.2. An odd element $\beta \in \mathcal{O}$ is *normalized* if $\beta \equiv 1 \pmod{2(1+i)}$.

Lemma 4.3. Let Λ_β be as above. Then $\Lambda_\beta \in \mathcal{O}[x]$ is monic of degree $|(\mathcal{O}/\beta\mathcal{O})^\times|$.

Proof. All that requires demonstration is $\Lambda_\beta \in \mathcal{O}[x]$. By Proposition 3.2, the roots of Λ_β are permuted under the action of $\text{Gal}(K_\beta/K)$ and hence the coefficients lie in the fixed field K of the Galois group. The roots of Λ_β are algebraic integers since they are also roots of the monic polynomial $xP_\beta(x^4) \in \mathcal{O}[x]$. It follows that $\Lambda_\beta(x) \in \mathcal{O}[x]$. \square

As cyclotomic polynomials provide a factorization of $x^n - 1$ over \mathbb{Q} , the lemnatomic polynomials provide a factorization of $xP_\beta(x^4)$ over K .

Proposition 4.4. Let $\beta \in \mathcal{O}$ be odd and let $xP_\beta(x^4)$ be the β -division polynomial from Theorem 2.1. Then

$$xP_\beta(x^4) = \prod_{\gamma|\beta} \Lambda_\gamma(x),$$

where the product is over all normalized divisors γ of β .

Proof. From Theorem 2.1, the roots of $xP_\beta(x^4)$ are $\varphi(\alpha\delta_\beta)$ for $[\alpha] \in \mathcal{O}/\beta\mathcal{O}$. The proof consists of using gcd's to reorganize the roots as in the analogous cyclotomic result. We refer the reader to [3, Proposition 9.1.5]. \square

We can also determine the constant term of Λ_β .

Proposition 4.5. Let $\beta \in \mathcal{O}$ be odd and a nonunit. If $\beta = u\pi^k$ where $u \in \mathcal{O}^\times$, π is a normalized prime, and $k \geq 1$, then $\Lambda_\beta(0) = \pi$. In all other cases, $\Lambda_\beta(0) = 1$.

Proof. We may assume that β is odd and normalized (this implies $i^\varepsilon = 1$ in part (1) of Theorem 2.1). Using $\varphi'(0) = 1$ and L'Hôpital's rule, we have

$$\beta = \lim_{x \rightarrow 0} \frac{\varphi(\beta x)}{\varphi(x)} = \lim_{x \rightarrow 0} \frac{P_\beta(\varphi(x)^4)}{Q_\beta(\varphi(x)^4)} = \frac{P_\beta(0)}{Q_\beta(0)} = P_\beta(0) \tag{13}$$

since $Q_\beta(0) = 1$ by part (5) of Theorem 2.1.

Now let π be a normalized odd prime. If $\beta = \pi$, then Proposition 4.4 tells us that $\Lambda_\pi(x) = P_\pi(x^4)$. Therefore, $\Lambda_\pi(0) = P_\pi(0) = \pi$ by (13).

Next, if $\beta = \pi^k$, then we proceed by strong induction. Suppose that for all $1 \leq k \leq n$, we have $\Lambda_{\pi^k}(0) = \pi$. From Proposition 4.4 and our induction hypothesis we obtain

$$\pi^{n+1} = P_{\pi^{n+1}}(0) = \prod_{k=1}^{n+1} \Lambda_{\pi^k}(0) = \pi^n \Lambda_{\pi^{n+1}}(0).$$

We conclude that $\Lambda_{\pi^{n+1}}(0) = \pi$, completing our induction.

Finally, suppose β is not a prime power. Again, [Proposition 4.4](#) tells us that

$$\beta = P_{\beta}(0) = \prod_{\substack{\gamma|\beta, \gamma \neq 1 \\ \gamma \text{ normalized}}} \Lambda_{\gamma}(0). \tag{14}$$

Each prime power π^k dividing β , where π is a normalized prime, contributes π to the product (14). Thus the normalized prime power divisors of β contribute a factor of β to (14). Therefore

$$\prod_{\substack{\gamma|\beta, \gamma \neq 1, \gamma \text{ normalized} \\ \gamma \text{ not a prime power}}} \Lambda_{\gamma}(0) = 1.$$

Using this and strong induction on the number of prime factors of β (counted with multiplicity), it is now easy to prove that $\Lambda_{\beta}(0) = 1$ when β is not a prime power. We leave the details to the reader. \square

Remark 4.6. The inspiration for [Proposition 4.5](#) derives from a similar result for irreducible factors of Chebyshev polynomials proved in [\[5, Proposition 2\]](#). We will explore the analogy between lemnatomic polynomials and Chebyshev polynomials in [Section 6](#).

We now come to the main result of this section.

Theorem 4.7. *If $\beta \in \mathcal{O}$ is odd, then the lemnatomic polynomial Λ_{β} is irreducible over K .*

Proof. We will follow the strategy used in [\[3, Theorem 9.1.9\]](#) to prove that the cyclotomic polynomial Φ_n is irreducible over \mathbb{Q} .

Since $\Lambda_{\beta} \in \mathcal{O}[x]$ is monic, Gauss’s lemma implies that an irreducible factor f of Λ_{β} in $K[x]$ lies in $\mathcal{O}[x]$, and we can assume that f is also monic. The roots of f have the form $\varphi(\alpha_i \delta_{\beta})$ for $\alpha_i \in \mathcal{O}$ with $\gcd(\alpha_i, \beta) = 1$ and $1 \leq i \leq r$ for some r . For $\pi \in \mathcal{O}$ an odd prime, consider the polynomial

$$f_{\pi}(x) = \prod_{i=1}^r (x - \varphi(\pi \alpha_i \delta_{\beta})).$$

Recall that $xP_{\beta}(x^4)$ is separable by [Theorem 2.1](#). It follows that Λ_{β} is separable over K and hence is separable modulo any prime of \mathcal{O} not dividing $\text{disc}(\Lambda_{\beta}) \neq 0$. For our purposes, we assume that the prime $\pi \in \mathcal{O}$ satisfies

(A) $\pi \equiv 1 \pmod{2(1+i)}$.

- (B) Λ_β is separable modulo π .
- (C) $\gcd(\pi, \beta) = 1$.

First, we show that $f_\pi \in \mathcal{O}[x]$. Let $\sigma \in \text{Gal}(K_\beta/K)$ and take a root $\varphi(\pi\alpha_i\delta_\beta)$ of f_π . Since $\alpha_i\delta_\beta$ and $\pi\alpha_i\delta_\beta$ are β -torsion generators, [Proposition 3.2](#) implies that there is $\gamma \in \mathcal{O}$ relatively prime to β such that

$$\sigma(\varphi(\alpha_i\delta_\beta)) = \varphi(\gamma\alpha_i\delta_\beta), \quad \sigma(\varphi(\pi\alpha_i\delta_\beta)) = \varphi(\gamma\pi\alpha_i\delta_\beta) = \varphi(\pi\gamma\alpha_i\delta_\beta). \tag{15}$$

Since $\varphi(\alpha_i\delta_\beta)$ is a root of $f \in \mathcal{O}[x]$, the left side of [\(15\)](#) implies that $\varphi(\gamma\alpha_i\delta_\beta)$ is a root as well. Then $\varphi(\pi\gamma\alpha_i\delta_\beta)$ is a root of f_π by definition. But this root is $\sigma(\varphi(\pi\alpha_i\delta_\beta))$ by the right side of [\(15\)](#). It follows that σ permutes the roots of f_π , and then $f_\pi(x) \in \mathcal{O}[x]$ follows easily.

We next prove the following claim:

$$f = f_\pi \quad \text{when } \pi \text{ satisfies (A), (B) and (C)}. \tag{16}$$

Suppose [\(16\)](#) is false. Since f and f_π are monic of the same degree and f is irreducible, $f \neq f_\pi$ implies that f is coprime to f_π . The roots of f_π are also roots of Λ_β , so there exists a monic $h \in \mathcal{O}[x]$ such that $\Lambda_\beta = f f_\pi h$. Let us analyze the roots of $f_\pi \pmod{\pi}$. From parts [\(5\)](#) and [\(6\)](#) of [Theorem 2.1](#), we have

$$\begin{aligned} P_\pi(x^4) &= x^{N(\pi)-1} + a_1x^{N(\pi)-5} + \cdots + a_{(N(\pi)-1)/4} \\ Q_\pi(x^4) &= a_{(N(\pi)-1)/4}x^{N(\pi)-1} + \cdots + a_1x^4 + 1, \end{aligned} \tag{17}$$

where π divides all the coefficients a_j . Let \mathcal{O}_{K_β} be the ring of integers of K_β and let \mathfrak{P} be a prime ideal of \mathcal{O}_{K_β} dividing $\pi\mathcal{O}_{K_\beta}$ and suppose that $\varphi(\alpha_i\delta_\beta)$ is a root of f . Therefore

$$\varphi(\pi\alpha_i\delta_\beta) = \varphi(\alpha_i\delta_\beta) \frac{P_\pi(\varphi(\alpha_i\delta_\beta)^4)}{Q_\pi(\varphi(\alpha_i\delta_\beta)^4)}$$

in K_β . By [\(17\)](#), we may reduce this equality modulo \mathfrak{P} to get

$$\varphi(\pi\alpha_i\delta_\beta) \equiv \varphi(\alpha_i\delta_\beta)^{N(\pi)} \pmod{\mathfrak{P}}. \tag{18}$$

Let

$$\tilde{f}_\pi(x) = \prod_{i=1}^r (x - \varphi(\alpha_i\delta_\beta)^{N(\pi)}).$$

Then an argument similar to that given for f_π shows that $\tilde{f}_\pi(x) \in \mathcal{O}[x]$. By [\(18\)](#), $f_\pi(x)$ and $\tilde{f}_\pi(x)$ have the same roots in $\mathcal{O}_{K_\beta}/\mathfrak{P}$ and hence

$$f_\pi \equiv \tilde{f}_\pi \pmod{\pi\mathcal{O}[x]}.$$

However, \tilde{f}_π is obtained from f by raising its roots to the $N(\pi)^{\text{th}}$ power, and a standard argument implies that

$$\tilde{f}_\pi \equiv f \pmod{\pi\mathcal{O}[x]}.$$

(See [3, Lemma 9.1.8] for the case of a prime $p \in \mathbb{Z}$. The proof for a prime $\pi \in \mathcal{O}$ is identical.) Combining these congruences shows that $f_\pi \equiv f \pmod{\pi\mathcal{O}[x]}$. Therefore,

$$\Lambda_\beta \equiv f f_\pi h \equiv f^2 h \pmod{\pi\mathcal{O}[x]},$$

which is to say that Λ_β is not separable modulo π . This contradicts our choice of π and allows us to conclude (16).

Now consider a root $\varphi(\alpha_i \delta_\beta)$ of f . Let η be the product of all odd primes dividing $\text{disc}(\Lambda_\beta)$ but not dividing β . If $\varphi(\gamma \delta_\beta)$ is any root of Λ_β , then the Chinese remainder theorem implies that there is a Gaussian integer ω such that

$$\omega \equiv \gamma \alpha_i^{-1} \pmod{\beta}, \quad \omega \equiv 1 \pmod{2(1+i)}, \quad \omega \equiv 1 \pmod{\eta}.$$

Therefore ω is odd and we may factor ω as $\omega = \pi_1 \cdots \pi_k$ for odd, normalized primes π_j coprime to $\beta \text{disc}(\Lambda_\beta)$. Iterating (16) we have

$$f = f_{\pi_1} = f_{\pi_1 \pi_2} = \cdots = f_{\pi_1 \cdots \pi_k}.$$

Hence

$$\varphi(\gamma \delta_\beta) = \varphi(\gamma \alpha_i^{-1} \alpha_i \delta_\beta) = \varphi(\omega \alpha_i \delta_\beta) = \varphi(\pi_1 \cdots \pi_k \alpha_i \delta_\beta)$$

is a root of $f_{\pi_1 \cdots \pi_k} = f$. Thus Λ_β and f have the same roots; since both are monic and separable they must be equal. We conclude that Λ_β is irreducible over K as desired. \square

Corollary 4.8. *Let $\beta \in \mathcal{O}$ be odd. Then*

$$\text{Gal}(K_\beta/K) \simeq (\mathcal{O}/\beta\mathcal{O})^\times.$$

In particular, if n is a positive, odd integer, then

$$\text{Gal}\left(K\left(\varphi\left(\frac{2\varpi}{n}\right)\right)/K\right) \simeq (\mathcal{O}/n\mathcal{O})^\times.$$

Proof. The elementary part of Proposition 3.2 gives an injection

$$\text{Gal}(K_\beta/K) \hookrightarrow (\mathcal{O}/\beta\mathcal{O})^\times$$

(see (11)). Since $K_\beta = K(\varphi(\delta_\beta))$, Theorem 4.7 and Lemma 4.3 tell us that

$$|\mathrm{Gal}(K_\beta/K)| = [K_\beta : K] = [K(\varphi(\delta_\beta)) : K] = \deg(\Lambda_\beta(x)) = |(\mathcal{O}/\beta\mathcal{O})^\times|.$$

Therefore, our injection must be an isomorphism. The final assertion follows since $K_n = K(\varphi(\frac{2\varpi}{n}))$ by definition. \square

The final assertion of [Corollary 4.8](#) completes the elementary proof of the isomorphism [\(3\)](#) from the introduction.

Remark 4.9. Let $\pi \in \mathcal{O}$ be an odd prime not dividing β , so that π is unramified in K_β . Under the isomorphism of [Corollary 4.8](#), some $\sigma \in \mathrm{Gal}(K_\beta/K)$ maps to $[\pi] \in (\mathcal{O}/\beta\mathcal{O})^\times$, where σ and π are linked via the equation

$$\sigma(\varphi(\delta_\beta)) = \varphi(\pi\delta_\beta).$$

If we assume in addition that $N(\pi)$ is relatively prime to the index $[\mathcal{O}_{K_\beta} : \mathcal{O}[\varphi(\delta_\beta)]]$, then [\(18\)](#) easily implies that

$$\sigma(u) \equiv u^{N(\pi)} \pmod{\mathfrak{P}}$$

for any $u \in \mathcal{O}_{K_\beta}$ and any prime \mathfrak{P} of \mathcal{O}_{K_β} dividing $\pi\mathcal{O}_{K_\beta}$. Since K_β/K is abelian, the Artin symbol $((K_\beta/K)/\pi)$ is the unique element of $\mathrm{Gal}(K_\beta/K)$ with this property. Hence we have proved that

$$\left(\frac{K_\beta/K}{\pi}\right)(\varphi(\delta_\beta)) = \varphi(\pi\delta_\beta),$$

which shows that the isomorphism $\mathrm{Gal}(K_\beta/K) \simeq (\mathcal{O}/\beta\mathcal{O})^\times$ from [Corollary 4.8](#) can be identified with the Artin map.

Observe the key role played by [\(18\)](#) here and in the proof of [Theorem 4.7](#). If you look back at the proof, you will see that [\(18\)](#) follows from [\(17\)](#). Proving [\(17\)](#) is actually the hardest part of the proof of [Theorem 4.7](#). The proof of [\(17\)](#) given in [[3, Theorem 15.4.8](#)] follows Eisenstein's original argument, which is both intricate and brilliant.

Example 4.10. Let us work out the case $n = 5$. The 5-division polynomial is

$$xP_5(x^4) = x^{25} + 50x^{21} - 125x^{17} + 300x^{13} - 105x^9 - 62x^5 + 5x.$$

We can factor 5 into normalized primes as $5 = (-1 + 2i)(-1 - 2i)$. Then

$$\begin{aligned} xP_5(x^4) &= \Lambda_1(x)\Lambda_{-1+2i}(x)\Lambda_{-1-2i}(x)\Lambda_5(x) \\ &= x(x^4 - 1 + 2i)(x^4 - 1 - 2i)(x^{16} + 52x^{12} - 26x^8 - 12x^4 + 1). \end{aligned}$$

Note that the constant terms of the factors are as predicted by [Proposition 4.5](#).

5. Abel's theorem on the lemniscate

Our work in the previous section allows us to give a new, concise proof of Abel's wonderful result about ruler and compass constructions on the lemniscate.

Theorem 5.1 (*Abel's theorem on the lemniscate*). *For a positive integer n , the n -division points of the lemniscate may be constructed using ruler and compass if and only if*

$$n = 2^k p_1 \cdots p_m,$$

where the p_i are distinct Fermat primes and k is a nonnegative integer.

Proof. We begin by reducing the equivalence. According to [3, Proposition 15.1.1], a point on the lemniscate is constructible if and only if its radial component is constructible. Therefore, constructing the n -division points is equivalent to constructing $\varphi(\frac{2\varpi a}{n})$ for $a = 1, \dots, n$. We need not worry about all these points, as [3, Corollary 15.2.7] states that if $\varphi(\frac{2\varpi}{n})$ is constructible, then $\varphi(\frac{2\varpi a}{n})$ is constructible for all $a \in \mathbb{Z}$. Finally, [3, Proposition 15.2.3] allows us to conclude that $\varphi(z)$ is constructible if and only if $\varphi(z/2)$ is constructible. Hence we may assume n is odd.

Next observe that $\Lambda_n \in \mathbb{Z}[x]$. This follows since lemnatomic polynomials satisfy $\overline{\Lambda_\beta} = \Lambda_{\bar{\beta}}$ with respect to complex conjugation. Then Λ_n is irreducible over \mathbb{Q} since it is irreducible over K by Theorem 4.7. Furthermore, $\varphi(\frac{2\varpi}{n})$ is a root of Λ_n since $\frac{2\varpi}{n}$ is an n -torsion generator (see the proof of Proposition 3.1). It follows that

$$\left[\mathbb{Q}\left(\varphi\left(\frac{2\varpi}{n}\right)\right) : \mathbb{Q} \right] = \deg(\Lambda_n) = |(\mathcal{O}/n\mathcal{O})^\times| = n^2 \prod_{p|n} \left(1 - \frac{1}{p}\right) \left(1 - \left(\frac{-1}{p}\right)\frac{1}{p}\right), \tag{19}$$

where the last equality follows from [4, Example 7.29].

Now assume that $\varphi(\frac{2\varpi}{n})$ is constructible. Then $[\mathbb{Q}(\varphi(\frac{2\varpi}{n})) : \mathbb{Q}]$ is a power of 2 by [3, Corollary 10.1.8], so that by (19), we have

$$2^m = n^2 \prod_{p|n} \left(1 - \frac{1}{p}\right) \left(1 - \left(\frac{-1}{p}\right)\frac{1}{p}\right).$$

Since n is odd, this implies that n is a product of distinct primes p . If $(-1/p) = -1$, then $(p-1)(p+1)$ is a power of 2, which forces $p = 3$, and if $(-1/p) = 1$, then $(p-1)^2$ is a power of 2, which easily implies that p is a Fermat prime.

Conversely, assume that n is a product of distinct Fermat primes. Observe that $\varphi(\frac{2\varpi}{n}) \in K(\varphi(\frac{2\varpi}{n})) = K_n$, which is Galois over \mathbb{Q} since K_n/K is Galois and $\varphi(\frac{2\varpi}{n})$ is real. Then (19) shows that

$$[K_n : \mathbb{Q}] = 2 \left[\mathbb{Q} \left(\varphi \left(\frac{2\varpi}{n} \right) \right) : \mathbb{Q} \right]$$

is a power of 2. Hence $\varphi\left(\frac{2\varpi}{n}\right)$ is constructible by [3, Theorem 10.1.12]. \square

Other proofs of this theorem are due to Abel, Eisenstein and Rosen, though Rosen was the first to prove the “only if” part of the theorem. Rosen’s proof [9] uses class field theory, while the above proof uses only the irreducibility of the lemnatomic polynomial A_n , which was proved without class field theory in Theorem 4.7. The proofs of Abel and Eisenstein are discussed in [3, Section 15.5], with references to the original papers. See also the book [7] by Prasolov and Solovyev.

6. Chebyshev polynomials

The analogy between Abel’s function $\varphi(z)$ and the sine function $\sin(\theta)$ has been recognized since the time of Gauss and Abel. For example, in his unpublished work on elliptic functions, Gauss wrote $\varphi(z)$ as $\sin \text{lemn}z$ (see [2]). Thus the analogy between lemnatomic polynomials and cyclotomic polynomials made earlier in this paper needs to be reconsidered from the point of view of the sine function. As we now show, the analog of the division polynomial $xP_\beta(x^4)$ is the well-known *Chebyshev polynomial* $T_n \in \mathbb{Z}[x]$, which is defined by the identity

$$\cos(n\theta) = T_n(\cos(\theta))$$

for a positive integer n .

Lemma 6.1. *If n is odd, then*

$$\sin(n\theta) = (-1)^{(n-1)/2} T_n(\sin(\theta)).$$

Furthermore, there is $S_n \in \mathbb{Z}[x]$ such that

$$T_n(x) = xS_n(x^2),$$

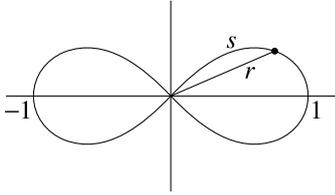
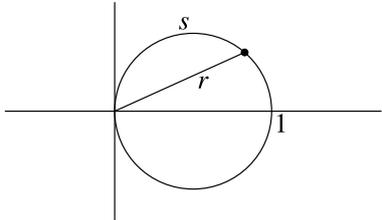
and the roots of $T_n(x) = xS_n(x^2)$ are $\sin(a\frac{2\pi}{n})$ for $[a] \in \mathbb{Z}/n\mathbb{Z}$.

Proof. Since n is odd, the addition laws for \sin and \cos imply that

$$\begin{aligned} \sin(n\theta) &= \cos\left(n\theta - \frac{\pi}{2}\right) = \cos\left(n\left(\theta - \frac{\pi}{2}\right) + \frac{n-1}{2}\pi\right) = \cos\left(n\left(\theta - \frac{\pi}{2}\right)\right) (-1)^{(n-1)/2} \\ &= (-1)^{(n-1)/2} T_n\left(\cos\left(\theta - \frac{\pi}{2}\right)\right) = (-1)^{(n-1)/2} T_n(\sin(\theta)). \end{aligned}$$

Table 1

The Lemniscate and the circle.

	Lemniscate	Circle
Polar equation	$r^2 = \cos(2\theta)$	$r = \cos(\theta)$
Graph		
Arc length	$s = \int_0^r \frac{dt}{\sqrt{1-t^4}}$	$s = \int_0^r \frac{dt}{\sqrt{1-t^2}}$
Inverse function	$r = \varphi(s)$	$r = \sin(s)$
Differential equation	$\varphi'(z)^2 + \varphi(z)^4 = 1$	$\cos(\theta)^2 + \sin(\theta)^2 = 1$
Multiplication map (β, n odd)	$\varphi(\beta z) = (-1)^\varepsilon \varphi(z) \frac{P_\beta(\varphi(z)^4)}{Q_\beta(\varphi(z)^4)}$	$\sin(n\theta) = (-1)^{(n-1)/2} \sin(\theta) S_n(\sin(\theta)^2)$
Galois group (β, n odd)	$\text{Gal}(K(\varphi(\frac{2\varpi}{\beta}))/K) \simeq (\mathcal{O}/\beta\mathcal{O})^\times$	$\text{Gal}(\mathbb{Q}(\sin(\frac{2\pi}{n}))/\mathbb{Q}) \simeq (\mathbb{Z}/n\mathbb{Z})^\times$

The formula for $\sin(n\theta)$ implies that 0 is a root of T_n . Since $\sin(n\theta)/\sin(\theta)$ is an even function, it follows that $T_n(x)/x$ is also even and hence is a polynomial in x^2 . The assertion concerning the roots of T_n is equally easy and is omitted. \square

Notice how $\sin(n\theta) = (-1)^{(n-1)/2} \sin(\theta) S_n(\sin(\theta)^2)$, n odd, is analogous to the formula for $\varphi(\beta z)$, β odd, from part (1) of [Theorem 2.1](#), where $n \equiv (-1)^{(n-1)/2} \pmod 4$ corresponds to $\beta \equiv i^\varepsilon \pmod{2(1+i)}$. Also, the crucial identity [\(12\)](#) used in the proof of [Proposition 3.2](#) is the lemniscatic analog of the identity $\cos(\theta - \frac{\pi}{2}) = \sin(\theta)$ used in the proof of [Lemma 6.1](#).

The analogy between $\varphi(z)$ and $\sin(\theta)$ actually begins with the equations $r^2 = \cos(2\theta)$ and $r = \cos(\theta)$ that define the lemniscate and circle of radius $1/2$ centered at $(1/2, 0)$. [Table 1](#) shows how these curves lead naturally to the functions $\varphi(z)$ and $\sin(\theta)$ and also records some of the similarities between their properties. (See also [\[6, 8.2\]](#) for another view of the analogy between $\varphi(z)$ and $\sin(\theta)$.)

This analogy suggests in particular that the lemnatomic polynomials A_β should correspond to the irreducible factors of the Chebyshev polynomial T_n when n is odd. The factors of T_n were studied by Hsiao [\[5\]](#) in 1984. Since T_n is not monic, he used the monic polynomial

$$C_n(x) = 2T_n(x/2) \in \mathbb{Z}[x].$$

Hsiao determines the irreducible factorization of C_n over \mathbb{Q} [\[5, Proposition 1\]](#). When n is odd, his result may be restated as a factorization

$$C_n = \prod_{k|n} D_k, \tag{20}$$

where D_n has degree $\phi(n)$ (the Euler ϕ -function) and is given by

$$D_n(x) = \prod_{[a] \in (\mathbb{Z}/n\mathbb{Z})^\times} \left(x - 2 \sin\left(a \frac{2\pi}{n}\right) \right). \tag{21}$$

Note the analogy with Definition 4.1. Thus, when n is odd, (20) is the analog of Proposition 4.4, where the irreducibility of D_n corresponds to the irreducibility of Λ_β proved in Theorem 4.7. Although Hsiao’s proof of irreducibility ultimately rests on the irreducibility of cyclotomic polynomials, we note that the polynomials D_n may be shown irreducible over \mathbb{Q} directly by adapting the proof of Theorem 4.7. We also note that in one of his unpublished papers, Schur [12, p. 423] mentions very briefly (without proof) the irreducible decomposition of Chebyshev polynomials

Hsiao also studied the constant term of the factors of C_n . When n is odd, his result can be stated as follows [5, Proposition 2].

Proposition 6.2. *Let $n \in \mathbb{Z}$ be odd and positive. If $n = p^k$ for a prime p , then $|D_n(0)| = p$. Otherwise, $D_n(0) = 1$.*

By tweaking Hsiao’s proof, one can show that when p is an odd prime and $k \geq 1$, we have $D_{p^k}(0) = (-1)^{(p-1)/2} p$. Since $(-1)^{(p-1)/2} p \equiv 1 \pmod{4}$, we see that $(-1)^{(p-1)/2} p$ is the analog of a normalized prime $\pi \in \mathcal{O}$, so that Proposition 6.2 is the analog of Proposition 4.5. In fact, Proposition 4.5 was inspired by Hsiao’s result.

Proposition 6.2 and (21) imply that $2 \sin(\frac{2\pi}{n})$ is a unit when $n > 1$ is odd and not a prime power. This is closely related to the standard fact that $1 - \zeta_n$ ($\zeta_n = e^{2\pi i/n}$) is a unit when $n > 1$ is not a prime power (see [14, Proposition 2.8]). To see why, note that $1 - \zeta_n = \zeta_{2n} \zeta_{2n}^{-1} - \zeta_{2n}^2 = -i \zeta_{2n} \cdot 2 \sin(\frac{\pi}{n})$.

For further results on the factorization of Chebyshev polynomials, see [8]. There is also another interesting analogy to consider, this one involving the Carlitz polynomials $[M](X)$ for $M \in \mathbb{F}_p[T][X]$. The irreducible factors of Carlitz polynomials have a lot in common with lemnatomic and cyclotomic polynomials. See [1] for more details.

For more on the history and number theory associated to the lemniscate, the reader should consult Schappacher’s article *Some Milestones of Lemniscatomy* [11].

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