

JOURNAL

de Théorie des Nombres
de BORDEAUX

anciennement Séminaire de Théorie des Nombres de Bordeaux

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Tome 17, n° 2 (2005), p. 517-525.

<http://jtnb.cedram.org/item?id=JTNB_2005__17_2_517_0>

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On the Galois group of generalized Laguerre polynomials

par FARSHID HAJIR

À Georges Gras, à l'occasion de son 60ème anniversaire

RÉSUMÉ. En utilisant la théorie des polygones de Newton, on obtient un critère simple pour montrer que le groupe de Galois d'un polynôme soit “grand.” Si on fixe $\alpha \in \mathbb{Q} - \mathbb{Z}_{<0}$, Filaseta et Lam ont montré que le Polynôme Généralisé de Laguerre $L_n^{(\alpha)}(x) = \sum_{j=0}^n \binom{n+\alpha}{n-j} (-x)^j / j!$ est irréductible quand le degré n est assez grand. On utilise notre critère afin de montrer que, sous ces hypothèses, le groupe de Galois de $L_n^{(\alpha)}(x)$ est soit le groupe alterné, soit le groupe symétrique, de degré n , généralisant des résultats de Schur pour $\alpha = 0, 1, \pm\frac{1}{2}, -1 - n$.

ABSTRACT. Using the theory of Newton Polygons, we formulate a simple criterion for the Galois group of a polynomial to be “large.” For a fixed $\alpha \in \mathbb{Q} - \mathbb{Z}_{<0}$, Filaseta and Lam have shown that the n th degree Generalized Laguerre Polynomial $L_n^{(\alpha)}(x) = \sum_{j=0}^n \binom{n+\alpha}{n-j} (-x)^j / j!$ is irreducible for all large enough n . We use our criterion to show that, under these conditions, the Galois group of $L_n^{(\alpha)}(x)$ is either the alternating or symmetric group on n letters, generalizing results of Schur for $\alpha = 0, 1, \pm\frac{1}{2}, -1 - n$.

1. Introduction

It is a basic problem of algebra to compute the Galois group of a given irreducible polynomial over a field K . If we order the monic degree n polynomials over \mathbb{Z} by increasing height, then the proportion which consists of irreducible polynomials with Galois group S_n tends to 1; for a more precise statement, see for example Gallagher [6]. Nevertheless, to prove that the Galois group of a given polynomial of degree n is S_n can be difficult if n is large. The algorithmic aspects of Galois group computations have witnessed a number of recent advances, for which an excellent reference is the special issue [18] of the Journal of Symbolic Computation, especially

Manuscrit reçu le 23 juin 2004.

Mots clefs. Galois group, Generalized Laguerre Polynomial, Newton Polygon.

This work was supported by the National Science Foundation under Grant No. 0226869.

the foreward by Matzat, McKay, and Yokoyama. Currently, for rational polynomials of degree up to 15, efficient algorithms are implemented, for instance, in GP-PARI and MAGMA. An important piece of any such algorithm is the collection of data regarding individual elements of the Galois group, for which the standard method is to factor the polynomial modulo various “good” primes (i.e. those not dividing its discriminant), obtaining the cycle-type of the corresponding Frobenius conjugacy classes in the Galois group.

Our first goal in this paper is to formulate a criterion which exploits the behavior of a given polynomial at “bad” primes for bounding the size of its Galois group from below. The criterion is especially efficacious if one suspects that a “medium size” prime (roughly between $n/2$ and n) is wildly ramified in the splitting field of the polynomial. The criterion we give (Theorem 2.2) follows quite simply from the theory of p -adic Newton Polygons; it is used in slightly less general form in Coleman [2] and is reminiscent of, but distinct from, a criterion of Schur [21, §1].

Our second goal is to illustrate the utility of the criterion by using it to calculate the Galois group for specializations of a certain one-parameter family of polynomials, which we now introduce. In the second volume of their influential and classic work [20], Pólya and Szegő define the Generalized Laguerre Polynomial (GLP)

$$L_n^{(\alpha)}(x) = \sum_{j=0}^n \binom{n+\alpha}{n-j} \frac{(-x)^j}{j!}.$$

The special case $\alpha = 0$ had appeared much earlier in the work of Abel [1, p. 284] and Laguerre [17], and the general case can in fact be found in Sonin [24, p. 41]. Shortly after the publication of [20], the study of the algebraic properties of this family of orthogonal polynomials was initiated by Schur [21], [22].

For instance, for the discriminant of the monic integral polynomial

$$\mathcal{L}_n^{(\alpha)}(x) := (-1)^n n! L_n^{(\alpha)}(x),$$

we have the following formula of Schur [22]:

$$(1.1) \quad \Delta_n^{(\alpha)} = \prod_{j=2}^n j^j (\alpha + j)^{j-1}.$$

In particular, if α is not in $[-n, -2] \cap \mathbb{Z}$, $L_n^{(\alpha)}(x)$ has no repeated roots. For $\alpha = 0, \pm 1/2, 1$, Schur [21], [22] established the irreducibility of all $L_n^{(\alpha)}(x)$ over \mathbb{Q} , and also showed that their Galois groups are as large as possible, namely A_n if $\Delta_n^{(\alpha)}$ is a rational square, and S_n otherwise.

A number of recent articles on the algebraic properties of GLP have appeared, including Feit [3], Coleman [2], Gow [9], Filaseta-Williams [5], Filaseta-Lam [4], Sell [23], Hajir [10], [11], and Hajir-Wong [12]. In particular, we have the following theorem of Filaseta and Lam [4] on the irreducibility of GLP.

Theorem. (Filaseta-Lam) *If α is a fixed rational number which is not a negative integer, then for all but finitely many integers n , $L_n^{(\alpha)}(x)$ is irreducible over \mathbb{Q} .*

In this paper, we provide a complement to the theorem of Filaseta and Lam by computing the Galois group of $L_n^{(\alpha)}(x)$ when n is large with respect to $\alpha \in \mathbb{Q} - \mathbb{Z}_{<0}$. Namely, we prove the following result.

Theorem 1.1. *Suppose α is a fixed rational number which is not a negative integer. Then for all but finitely many integers n , the Galois group of $L_n^{(\alpha)}(x)$ is A_n if $\Delta_n^{(\alpha)}$ is a square and S_n otherwise.*

Remarks. 1. The hypothesis that α not be a negative integer is necessary, as in that case, $L_n^{(\alpha)}(x)$ is divisible by x for $n \geq |\alpha|$. For a study of the algebraic properties of $L_n^{(\alpha)}(x)$ for $\alpha \in \mathbb{Z}_{<0}, n < |\alpha|$, see [10], [23] and [11]. In the latter work, Theorem 2.2 is used to prove that A_n is contained in the Galois group of $L_n^{(-n-r)}$ for all large enough (with respect to n) positive integers r .

2. Using a different set of techniques, the following companion to Theorem 1.1 is proved in [12]: If we fix $n \geq 5$ and a number field K , then for all but finitely many $\alpha \in K$, $L_n^{(\alpha)}(x)$ is irreducible and has Galois group A_n or S_n over K . For each $n \leq 4$, infinitely many \mathbb{Q} -reducible specializations exist, and for $n = 4$, there are infinitely many specializations which are irreducible but have D_4 -Galois group over \mathbb{Q} , cf. [11, Section 6].

3. For integral α , some cases where $\Delta_n^{(\alpha)}$ is a square (giving Galois group A_n) are

- $\alpha = 1$ and $n \equiv 1 \pmod{2}$ or $n + 1$ is an odd square ([22]),
- $\alpha = n$, and $n \equiv 2 \pmod{4}$ ([9], it is not yet known if all of these polynomials are irreducible [5]),
- $\alpha = -1 - n$, and $n \equiv 0 \pmod{4}$ ([21], [2]),
- $\alpha = -2 - n$, and $n \equiv 1 \pmod{4}$ ([10]).
- $\alpha = -3 - n$, and $n + 1$ is an odd square ([23]).

See [11, §5] as well as the above-cited papers for more details.

4. The proofs of the Filaseta-Lam Theorem in [4] and of Theorem 1.1 are both effective.

Acknowledgements. I would like to thank the organizers, Christian Maire, Jean-Robert Belliard and Hassan Oukhaba, for having invited me to speak at the Fall 2003 Conference in honor of Georges Gras at the University of Franche-Comté. I am also grateful to the anonymous referee for a careful reading and comments which improved the paper.

2. A criterion for having large Galois group

2.1. Newton Polygons. Let K be a field equipped with a discrete valuation v and a corresponding completion K_v . We assume v is normalized, i.e. $v(K^*) = \mathbb{Z}$, and employ the same letter v to denote an extension of this valuation to an algebraic closure $\overline{K_v}$ of K_v .

For a polynomial $f(x) = a_n x^n + a_{n-1} x^{n-1} + \cdots + a_0 \in K[x]$ with $a_0 a_n \neq 0$, the v -adic Newton Polygon of $f(x)$, denoted $NP_v(f)$, is defined to be the lower convex hull of the set of points

$$S_v(f) = \{(0, v(a_0)), (1, v(a_1)), \dots, (n, v(a_n))\}.$$

It is the highest polygonal line passing on or below the points in $S_v(f)$. The points where the slope of the Newton polygon changes (including the rightmost and leftmost points) are called the *corners* of $NP_v(f)$; their x -coordinates are the *breaks* of $NP_v(f)$.

For the convenience of the reader, we recall the main theorem about v -adic Newton Polygons; for a proof see, for instance, Gouvêa [8]. A very nice survey of the uses of the Newton Polygon for proving irreducibility is Mott [19]. For generalizations to several variables, see Gao [7] and references therein. For a recent paper on using Newton Polygons to compute Galois groups, see Kölle-Schmid [15].

Theorem 2.1 (Main Theorem of Newton Polygons). *Suppose $f(x) \in K[x]$ is not divisible by x . Let $(x_0, y_0), (x_1, y_1), \dots, (x_r, y_r)$ denote the successive vertices of $NP_v(f)$, with slopes $m_i = (y_i - y_{i-1}) / (x_i - x_{i-1})$. Then there exist polynomials f_1, \dots, f_r in $K_v[x]$ such that*

- i) $f(x) = f_1(x)f_2(x) \cdots f_r(x)$,
- ii) for $i = 1, \dots, r$, the degree of f_i is $x_i - x_{i-1}$,
- iii) for $i = 1, \dots, r$, all the roots of f_i in $\overline{K_v}$ have v -adic valuation $-m_i$.

2.2. Newton Index. We now suppose that K is a fixed global field, i.e. K is a finite extension of \mathbb{Q} (number field case) or of $\mathbb{F}(T)$, where \mathbb{F} is a finite field (function field case). A global field K enjoys the property that for a given element $\alpha \in K$, $v(\alpha) = 0$ for all but finitely many valuations v of K .

Definition. Given $f \in K[x]$ and λ a linear polynomial in $K[x]$, we define the v -Newton Index of f at λ , $\mathcal{N}_v(f, \lambda)$, to be the least common multiple of the denominators (in lowest terms) of all slopes of $NP_v(f \circ \lambda)$. The *Newton*

Index of f over K , $\mathcal{N}(f)$, is defined to be the least common multiple of all $\mathcal{N}_v(f, \lambda)$ as v runs over the non-archimedean places of K and λ runs over the linear polynomials in $K[x]$.

Some comments on this definition are in order. It is clear that, for each v and λ , $\mathcal{N}_v(f, \lambda)$ is a divisor of $\text{lcm}(1, 2, \dots, n)|n|!$ where n is the degree of f , hence the same is true for $\mathcal{N}(f)$. Thus, the Newton index of f over K is a well-defined divisor of $n!$. It is not clear from its definition, however, that it is effectively computable; we make some comments on this in the following Lemma. For the applications we have in mind, it will suffice to look for a single suitable pair v, λ such that $\mathcal{N}_v(f, \lambda)$ is divisible by a prime $p \in (n/2, n - 2)$, but we have formalized the concept of Newton Index in order to demonstrate the possibilities and limitations of this approach for future applications.

Lemma 2.1. *Let K_f be a splitting field for f over K , and let R_f be the (finite) set of non-archimedean places of K that ramify in K_f . Then*

$$\mathcal{N}(f) = \text{lcm}_{v \in R_f} \text{lcm}_{b \in K_v} \mathcal{N}_v(f, x + b).$$

Proof. Let us first note that for any linear $K[x]$ -polynomial λ , K_f is a splitting field for $f \circ \lambda$. Now, if an integer $d > 1$ divides the denominator of some slope of $NP_v(f \circ \lambda)$, then v is ramified in K_f/K (see the proof of Theorem 2.2). This shows that $\mathcal{N}(f)$ is the least common multiple of $\mathcal{N}_v(f, \lambda)$ as v runs over R_f and λ runs over linear $K[x]$ -polynomials.

It remains only to show that for each v , we can restrict this to the least common multiple over *monic* $K_v[x]$ -polynomials λ . To see this, suppose $\lambda(x) = ax + b$ and $\lambda_1(x) = x + b$ (with $a \in K^*, b \in K$) so that $(f \circ \lambda)(x) = (f \circ \lambda_1)(ax)$. Let $h = f \circ \lambda_1$ and $g = f \circ \lambda$. Note that if $h(x) = \sum_{j=0}^n b_j x^j$ and $g(x) = h(ax) = \sum_{j=0}^n b'_j x^j$, then the set of slopes of $NP_v(g)$ is simply a shift of that of $NP_v(h)$ by $v(a)$, because for all $0 \leq j < k \leq n$,

$$\frac{v(b'_j) - v(b'_k)}{j - k} = v(a) + \frac{v(b_j) - v(b_k)}{j - k}.$$

Since $v(K^*) = \mathbb{Z}$, it follows that the slopes of $NP_v(h)$ and $NP_v(g)$ have the same denominators. Thus, $\mathcal{N}_v(f, \lambda) = \mathcal{N}_v(f, \lambda_1)$, giving the desired conclusion. □

According to the preceding Lemma, we would have an effective procedure for calculating $\mathcal{N}(f)$ if we could solve the following problem.

Problem. Give an algorithm for calculating

$$\mathcal{N}_v(f) := \text{lcm}_{b \in K_v} \mathcal{N}_v(f, x + b).$$

We now formulate a criterion for an irreducible polynomial to have “large” Galois group. The key idea appears in Coleman’s computation [2] of the Galois group of the n th Taylor polynomial of the exponential function, which incidentally is the GLP $(-1)^n L_n^{(-1-n)}(x)$.

Theorem 2.2. *Suppose K is a global field and $f(x)$ is an irreducible polynomial in $K[x]$. Then \mathcal{N}_f divides the order of the Galois group of f over K . Moreover, if \mathcal{N}_f has a prime divisor ℓ in the range $n/2 < \ell < n - 2$, where n is the degree of f , then the Galois group of f contains A_n , in which case, this Galois group is A_n if $\text{disc}(f)$ is a square in K^* and S_n otherwise.*

Proof. Suppose v is a valuation of K , λ is a linear $K[x]$ -polynomial, and q is an arbitrary divisor of the denominator of some slope s of $NP_v(g)$ where $g = f \circ \lambda$. Clearly, g is irreducible and has the same Galois group as f . It suffices to show that q divides the order of the Galois group of g over K . By Theorem 2.1, there exists a root $\alpha \in \overline{K}_v$ of g with valuation $-s$. Since q divides the denominator of s , q divides the ramification index e of $K_v(\alpha)/K_v$ ([8, Proposition 5.4.2]). But e divides the degree $[K_v(\alpha) : K_v]$, which in turn divides the order of the Galois group of g over K_v , hence also over K . If $q = \ell$ is a prime in the interval $(n/2, n - 2)$, then the Galois group of g contains an ℓ -cycle, so it must contain A_n by a theorem of Jordan [14] (or see, for instance, Hall’s book [13, Thm 5.6.2 and 5.7.2]). It is well-known that the Galois group over K of an irreducible polynomial of degree n is contained in A_n if and only if its discriminant is a square in K^* . \square

Remark. Schur proved a similar result ([21, §1, III]), namely, if the discriminant of a number field K of degree n is divisible by p^n , then the Galois closure L of K has degree $[L : \mathbb{Q}]$ divisible by p . In general, if p divides the discriminant of an irreducible polynomial f , it is not easy to determine the p -valuation of the discriminant of the stem field $\mathbb{Q}[x]/(f)$; thus, each of Theorem 2.2 and Schur’s criterion can be useful depending on whether we have information about the discriminant of the field or that of the defining polynomial. Neither criterion is useful when the discriminant of f is square-free, for example, since in that case, all the non-trivial ramification indices are 2. On the other hand, over base field \mathbb{Q} , irreducible polynomials with square-free discriminant also have Galois group S_n see e.g. Kondo [16]; the proof of this fact uses the triviality of the fundamental group of \mathbb{Q} .

3. Proof of Theorem 1.1

We now let $K = \mathbb{Q}$. For a prime p , we write NP_p in place of NP_v where $v = \text{ord}_p$ is the p -adic valuation of \mathbb{Q} .

Lemma 3.1. *Suppose p is a prime in the interval $(n/2, n - 2)$, and $f(x) = \sum_{j=0}^n \binom{n}{j} c_j x^j \in \mathbb{Q}[x]$ is an irreducible polynomial of degree n over \mathbb{Q} with p -integral coefficients, i.e. $\text{ord}_p(c_j) \geq 0$ for $j = 0, \dots, n$. Suppose further that*

- i) $\text{ord}_p(c_0) = 1$,
- ii) $\text{ord}_p(c_j) \geq \text{ord}_p(c_0)$ for $1 \leq j \leq n - p$,
- iii) $\text{ord}_p(c_p) = 0$.

*Then, p divides the order of the Galois group of f over \mathbb{Q} . Indeed, this Galois group is A_n if $\text{disc}(f) \in \mathbb{Q}^{*2}$ and S_n otherwise.*

Proof. It is easy to check that $\binom{n}{j}$ is divisible by p if and only if $n - p + 1 \leq j \leq p - 1$. The given assumptions then guarantee that $(0, \text{ord}_p(c_0))$ and $(p, 0)$ are the first two corners of $NP_p(f)$. Therefore, $-\text{ord}_p(c_0)/p$ is a slope of $NP_p(f)$. It follows from i) that $p \mid \mathcal{N}_f$, and we are done by Theorem 2.2. □

Remark. It is easy to see that the Lemma holds for $p \in (1 + n/2, n - 2)$ if we replace i) with i') $1 \leq \text{ord}_p(c_0) \leq p/(2p - n - 1)$.

We are now ready to prove the Main Theorem.

Proof of Theorem 1.1. We write $\alpha = \lambda/\mu$ in lowest terms, i.e. with $\mu \geq 1$ and $\text{gcd}(\lambda, \mu) = 1$. By assumption, α is not a negative integer. We will work with the normalized (monic, integral) polynomial

$$f(x) = \mu^n n! L_n^{(\lambda/\mu)}\left(\frac{-x}{\mu}\right) = \sum_{j=0}^n \binom{n}{j} (n\mu + \lambda)((n-1)\mu + \lambda) \cdots ((j+1)\mu + \lambda) x^j.$$

We wish to apply Lemma 3.1 to it, so we let

$$(3.1) \quad c_j = \prod_{k=j+1}^n (k\mu + \lambda), \quad 0 \leq j \leq n,$$

and seek an appropriate prime p , i.e. one satisfying the conditions of the Lemma.

By a suitably strong form of Dirichlet’s theorem on primes in arithmetic progressions, there exists an effective constant $D(\mu)$ such that if $x \geq D(\mu)$ and $h \geq x/(2 \log^2 x)$, the interval $[x - h, x]$ contains a prime in the congruence class $\lambda \pmod{\mu}$ (see Filaseta-Lam [4, p. 179]). Taking $x = n - 3 \geq D(\mu)$, we find that for some integer $\ell \in [1, n]$, $p = \mu\ell + \lambda$ is a prime satisfying

$$(3.2) \quad \frac{n\mu + \mu + \lambda}{\mu + 1} \leq p \leq n - 3,$$

as long as

$$\frac{1 - 3/n}{2 \log^2(n - 3)} + \frac{3 + (\mu + \lambda)/(\mu + 1)}{n} \leq \frac{1}{\mu + 1},$$

which clearly holds for all n large enough with respect to λ, μ .

We now fix a prime $p = \mu\ell + \lambda$ satisfying (3.2). For such a prime p , let us check the hypotheses of Lemma 3.1. We have $(n\mu + \mu + \lambda)/(\mu + 1) > n/2$ if and only if

$$(3.3) \quad n(\mu - 1) > -2\mu - 2\lambda.$$

Since α is not a negative integer, if $\mu = 1$, then $\lambda \geq 0$, so (3.3) holds for all n . If $\mu > 1$, we simply need to take $n > -2(\mu + \lambda)/(\mu - 1)$ in order to achieve $n/2 < p < n - 2$. Our c_j are integral so our polynomial is p -integral for every prime p . Before we discuss the p -adic valuations of the coefficients c_j , let us note that in the congruence class $\lambda \pmod{\mu}$, the smallest multiple of p larger than p is $(\mu + 1)p$, and, similarly, the largest multiple of p in this congruence class which is less than p is $(-\mu + 1)p$. Now we claim that, for n large enough, we have

$$(3.4) \quad (-\mu + 1)p < \lambda + \mu$$

as well as

$$(3.5) \quad \lambda + \mu n < (\mu + 1)p.$$

Indeed, if $\mu = 1$, then (3.4) holds for all n , while for $\mu \geq 2$, $n \geq -2\lambda$ implies (3.4); moreover, (3.5) is a direct consequence of (3.2). From (3.4), (3.5) and (3.1), we then read off that $\text{ord}_p(c_j) = 1$ for $0 \leq j \leq \ell - 1$, and $\text{ord}_p(c_j) = 0$ for $\ell \leq j \leq n$. One easily checks that (3.4) and (3.5) give exactly $p > \ell - 1$ and $n - p < \ell$, i.e. conditions ii) and iii) of Lemma 3.1 hold. By Filaseta-Lam [4], there is an effectively computable constant $N(\alpha)$ such that $f(x)$ is irreducible for $n \geq N(\alpha)$. Thus, all the conditions of Lemma 3.1 hold, and the proof of the theorem is complete. \square

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