DEGREE 14 2-ADIC FIELDS

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Abstract. We study the 590 nonisomorphic degree 14 extensions of the 2-adic numbers by computing defining polynomials for each extension as well as basic invariant data for each polynomial, including the ramification index, residue degree, discriminant exponent, and Galois group. Our study of the Galois groups of these extensions shows that only 10 of the 63 transitive subgroups of $S_{14}$ occur as a Galois group. We end by describing our implementation for computing Galois groups in this setting, which is of interest since it uses subfield information, the discriminant, and only one other resolvent polynomial.

1. Introduction

Hensel’s $p$-adic numbers are a foundational tool in 21st century number theory, with applications to such areas as number fields, elliptic curves, and representation theory (among others). They are also the subject of much current research themselves, with several studies aimed at classifying arithmetic invariants of finite extensions of the $p$-adic numbers. Among the most useful invariants to identify are the ramification index, residue degree, discriminant, and Galois group (of the normal closure) of each extension. For such a pursuit, we can take the following classical result as motivation [13, p. 54].

Theorem 1.1. For a fixed prime number $p$ and positive integer $n$, there are only finitely many nonisomorphic extensions of the $p$-adic numbers of degree $n$.

When $p \nmid n$, then all extensions are tamely ramified and are well understood [10]. Likewise, when $p = n$ the situation has been solved since the early 1970s [1, 10]. The difficult cases where $p \mid n$ and $n$ is composite have been dealt with on a case-by-case basis for low-degrees $n$ and small primes $p$. Jones and Roberts have classified the cases where $n \leq 10$ [9, 10, 11], and the first author has worked on degree 12 [3, 4, 5, 6].

In this paper, we are concerned with classifying degree 14 extensions of the 2-adic numbers. In particular, we focus on computing defining polynomials for each field as well as the Galois group for each of these polynomials. The other invariants are straightforward to compute using basic number field commands in [19]. In section 2, we lay the theoretical groundwork for computing Galois groups of $p$-adic fields using the theory of ramification groups. A consequence of this section is that every degree 14 extension of $\mathbb{Q}_2$ has a unique septic subfield. In section 3, we use the result of section 2 to compute defining polynomials. In the final section, we discuss our method of determining the Galois groups of the polynomials found in section 3.

2000 Mathematics Subject Classification. Primary 11S15, 11S20.

Key words and phrases. 2-adic, extension fields, Galois group, local field.
2. Ramification Groups

The aim of this section is to show that every degree 14 2-adic field has a unique septic subfield. We accomplish this by introducing the basic properties of ramification groups, and we use those properties to deduce structural information about degree 14 extensions of $\mathbb{Q}_2$. A more detailed exposition of ramification group theory can be found in [16].

Definition 2.1. Let $L/\mathbb{Q}_p$ be a Galois extension with Galois group $G$. Let $v$ be the discrete valuation on $L$ and let $\mathbb{Z}_L$ denote the corresponding discrete valuation ring. For an integer $i \geq -1$, we define the $i$-th ramification group of $G$ to be the following set

$$G_i = \{ \sigma \in G : v(\sigma(x) - x) \geq i + 1 \text{ for all } x \in \mathbb{Z}_L \}$$

The ramification groups define a sequence of decreasing normal subgroups which are eventually trivial and which give structural information about the Galois group of a $p$-adic field. For example, the following result is useful for determining possible Galois groups of $p$-adic fields. A proof can be found in [16, Ch. 4].

Lemma 2.2. Let $L/\mathbb{Q}_p$ be a Galois extension with Galois group $G$, and let $G_i$ denote the $i$-th ramification group. Let $\mathfrak{p}$ denote the unique maximal ideal of $\mathbb{Z}_L$ and $U_0$ the units in $L$. For $i \geq 1$, let $U_i = 1 + \mathfrak{p}^i$.

(a) For $i \geq 0$, $G_i/G_{i+1}$ is isomorphic to a subgroup of $U_i/U_{i+1}$.
(b) The group $G_0/G_1$ is cyclic and isomorphic to a subgroup of the group of roots of unity in the residue field of $L$. Its order is prime to $p$.
(c) The quotients $G_i/G_{i+1}$ for $i \geq 1$ are abelian groups and are direct products of cyclic groups of order $p$. The group $G_1$ is a $p$-group.
(d) The group $G_0$ is the semi-direct product of a cyclic group of order prime to $p$ with a normal subgroup whose order is a power of $p$.
(e) The groups $G_0$ and $G$ are both solvable.

Suppose $f$ is an irreducible polynomial of degree 14 defined over $\mathbb{Q}_2$ and let $G$ be its Galois group. From Lemma 2.2, we see that $G$ is a solvable transitive subgroup of $S_{14}$. Furthermore, $G$ contains a solvable normal subgroup $G_0$ such that $G/G_0$ is cyclic. The group $G_0$ contains a normal subgroup $G_1$ such that $G_1$ is a 2-group (possibly trivial). Moreover, $G_0/G_1$ is cyclic of order dividing $2^{[G:G_0]} - 1$. Direct computation on the 63 transitive subgroups of $S_{14}$ (using [7] for example) shows that only 15 of the 63 are possibilities for the Galois group of $f$. Using the transitive group notation in [7], these 15 groups are $\text{TransitiveGroup}(14,n)$, where $n$ is one of the following possibilities:

$$\{1, 4, 5, 6, 7, 9, 11, 18, 21, 29, 35, 40, 41, 44, 48\}.$$

Showing that every degree 14 extension of $\mathbb{Q}_2$ has a unique septic subfield amounts to showing that each of the above 15 groups possesses the corresponding group-theoretic property. In particular, let $K/\mathbb{Q}_2$ be a degree 14 extension defined by an irreducible polynomial $f$, and consider the subfields of $K$ up to isomorphism. The list of the Galois groups of the Galois closures of the proper nontrivial subfields of $K$ is important for our work. We call this the subfield Galois group content of $K$, and we denote it by $\text{sgg}(K)$.

The $\text{sgg}$ content of an extension is an invariant of its Galois group. Indeed, suppose the normal closure of $K/\mathbb{Q}_2$ has Galois group $G$ and let $E$ be the subgroup
Table 1. Septic Extensions of Q₂, including the ramification index e and Galois group G of a defining polynomial poly

<table>
<thead>
<tr>
<th>e</th>
<th>G</th>
<th>poly</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7T1</td>
<td>(x' - x + 1)</td>
</tr>
<tr>
<td>7</td>
<td>7T3</td>
<td>(x^7 - 2)</td>
</tr>
</tbody>
</table>

fixing \(K\). By Galois theory, the nonisomorphic subfields of \(K\) correspond to the intermediate subgroups \(F\), up to conjugation, such that \(E \leq F \leq G\). Specifically, if \(K'\) is a subfield and \(F\) is its corresponding intermediate group, then the Galois group of the normal closure of \(K'\) is equal to the permutation representation of \(G\) acting on the cosets of \(F\) in \(G\). Consequently, it makes sense to speak of the sgg content of a transitive subgroup as well.

For each of these 15 groups, we used [7] to compute their sgg contents. We found that 5 of these groups – 4, 7, 40, 41, 48 – had 7T4 in their sgg content. This means that polynomials whose Galois group is one of these 5 possibilities must define an extension with a septic subfield whose normal closure has Galois group 7T4. But as we will see in the next section, the only possible Galois groups of degree 7 polynomials over Q₂ are either 7T1 or 7T3. This means that these 5 groups cannot occur as the Galois group of a degree 14 2-adic field.

Therefore, there are only 10 possible Galois groups of degree 14 extensions of Q₂. For each of these possible Galois groups, Table 3 shows their respective sgg contents. Notice that each group has exactly one entry of the form 7Tj. This shows that degree 14 extensions of Q₂ have a unique septic subfield.

3. Defining Polynomials

As a consequence of Section 2, every degree 14 extension of Q₂ can be realized uniquely as a quadratic extension of a septic 2-adic field. Defining polynomials for degree 14 2-adic fields are therefore straightforward to compute.

First, we compute all septic 2-adic fields. Such fields are tamely ramified and are therefore easy to classify using [10]. Table 1 shows that there are two septic 2-adic fields, the unramified extension (with cyclic Galois group) and a totally ramified extension (with 7T3 = C₇ : C₃ as its Galois group). Next, for each septic 2-adic field, we compute all of its quadratic extensions using [2]. In each case, there are 511 such quadratic extensions. But some of these 1022 extensions are isomorphic. Using Panayi's algorithm [15], we discard isomorphic extensions to find a total of 590 nonisomorphic degree 14 extensions of Q₂. Polynomials are available on request by emailing the first author.

Table 2 contains numerical data on the numbers of these extensions, excluding the unramified extensions of the two septic 2-adic fields. The Base column references the two polynomials in Table 1. The column e is the discriminant exponent, G is the Galois group of the defining polynomial, and \(\#Q^{14}_2\) is the number of non-isomorphic extensions over Q₂. Notice that there are 78 extensions that are ramified quadratic extensions of the unramified septic 2-adic field. There are 510 ramified quadratic extensions of the unique totally ramified septic 7-adic field. These 588 extensions plus the unramified extensions of the two septic 2-adic fields gives 590 total degree 14 extensions of Q₂. Krasner’s mass formula [12] verifies that
these are all such extensions. We note that the number of extensions can also be verified using an implementation of [15] in [19].

4. Galois Groups

It remains to identify the Galois group over \( \mathbb{Q}_2 \) for each of the 590 polynomials. We follow the standard approach for determining Galois groups [8]. We compute enough group-theoretic and field-theoretic invariants so as to uniquely identify a polynomial with its corresponding Galois group. Our strategy is to divide the above list of 10 groups into smaller pieces that are easily distinguished from each other. Our first division will be at the level of centralizer order. The order of the centralizer in \( S_{14} \) of the Galois group is useful as it corresponds to the size of the automorphism group of the stem field defined by the polynomial. We divide these smaller sets even further based on their \( sgg \) content and their parity. The parity of a group \( G \) is +1 if \( G \cong A_{14} \) and −1 otherwise. Likewise, the parity of a polynomial \( f \) is +1 if its discriminant is a square in \( \mathbb{Q}_2 \) and −1 otherwise. When this information is not enough, we introduce a single resolvent polynomial [18], and use information about its irreducible factors over \( \mathbb{Q}_2 \). This resolvent, denoted as \( f_{364} \), has degree 364. It corresponds to the subgroup \( S_{11} \times S_3 \) of \( S_{14} \) and can be computed as a linear resolvent on 3-sets [17]; i.e., as a resultant. It can also be computed in the following way. Let \( f(x) \) define a degree 14 extension over \( \mathbb{Q}_2 \), and let \( r_1, r_2, \ldots, r_{14} \) be the roots of \( f \). Then,

\[
f_{364}(x) = \prod_{i=1}^{12} \prod_{j=i+1}^{13} \prod_{k=j+1}^{14} (x - r_i - r_j - r_k).
\]
Table 3. Invariant data for possible Galois groups of degree 14 2-adic fields.

| G   | Parity | $|C_{S_{14}}(G)|$ | sgg  | $f_{364}$               | Quad Subs | $\#Q_2^{14}$ |
|-----|--------|------------------|------|------------------------|-----------|-------------|
| 14T1 | −1     | 14               | 2T1,7T1 | 2T1,7T3               | 7         | 7           |
| 14T5 | −1     | 2                | 2T1,7T3 | 2T1,7T3               | 7         | 7           |
| 14T6 | +1     | 2                | 7T1   | 14^6, 28^2, 56^4     | 2         |             |
| 14T21| +1     | 2                | 7T1   | 14^6, 56^5            | 7         |             |
| 14T9 | −1     | 2                | 7T1   | 14^6, 56^5            | one       | 14          |
| 14T29| −1     | 2                | 7T1   | 14^6, 56^5            | none      | 49          |
| 14T11| +1     | 2                | 7T3   | 28^2, 42^2, 56, 168  | 14         |             |
| 14T35| +1     | 2                | 7T3   | 42^2, 56^2, 168      | 49         |             |
| 14T18| −1     | 2                | 7T3   | 42^2, 56^2, 168      | one       | 98          |
| 14T44| −1     | 2                | 7T3   | 42^2, 56^2, 168      | none      | 343         |

We note that in our search for suitable resolvent polynomials, we also looked at a lower degree linear resolvent (corresponding to the group $S_2 \times S_{12}$), subfields of the field defined by this lower degree resolvent, and other subfield information of $f_{364}$. In order to keep the computational difficulty of our algorithm as low as possible, we focused on subfields of degree less than 12, with a preference toward quadratic subfields of the fields defined by the irreducible factors of the linear resolvents. Under these constraints, we found the degree 56 factors of $f_{364}$ to be the smallest degree factors that accomplished our needs.

Table 3 contains all pertinent invariant data for each Galois group. Notice that all groups can be distinguished using parity, centralizer order, sgg content, and the degrees of the factors of $f_{364}$ except for two sets: 14T9/14T29 and 14T18/14T44. But in both cases, the groups can be distinguished by counting quadratic subfields of the fields defined by the degree 56 factors of $f_{364}$. In these two cases, we have also verified Galois group computations with [14] by computing sizes of splitting fields. As before, we include the column $\#Q_2^{14}$, which represents the number of non-isomorphic extensions over $\mathbb{Q}_2$ with the corresponding Galois group (which can also be inferred from Table 2). The other columns are defined as follows: $|C_{S_{14}}(G)|$ gives the size of the centralizer of the group in $S_{14}$, sgg gives the sgg content of the group, $f_{364}$ gives the degrees of the irreducible factors of $f_{364}$, and Quad Subs gives the number of quadratic subfields of the fields defined by the degree 56 factors of $f_{364}$.

On our workstation – two quad-core Intel Xeon processors (2.4GHz) – our Galois group computations finished in just over 4 months (125 days). The most difficult cases (where the Galois group was either 14T9/14T29 or 14T18/14T44) took on average 20–25 hours per polynomial.

5. ACKNOWLEDGEMENTS

The authors wish to thank the anonymous referee for their careful reading and useful comments, Sebastian Pauli for helpful discussions, Elon University for supporting this project through internal grants, and the Center for Undergraduate Research in Mathematics for their support.
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