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ON p-RATIONALITY OF NUMBER FIELDS. APPLICATIONS – PARI/GP PROGRAMS

by

Georges Gras

Abstract. — Let $K$ be a number field. We prove that its ray class group modulo $p^2$ (resp. $8$) if $p > 2$ (resp. $p = 2$) characterizes its $p$-rationality. Then we give two short and very fast PARI Programs (Sections 3.1, 3.2) testing if $K$ (defined by an irreducible monic polynomial) is $p$-rational or not. For quadratic fields we verify some densities of 3-rational fields related to Cohen–Lenstra–Martinet ones and analyse Greenberg’s conjecture on the existence of $p$-rational fields with Galois groups $(\mathbb{Z}/2\mathbb{Z})^t$ needed for the construction of some Galois representations with open image. We give examples for $p = 3$, $t = 5$ and $t = 6$ (Sections 5.1, 5.2) and illustrate other approaches (Pitoun–Varescon, Barbulescu–Ray). We conclude about the existence of imaginary quadratic fields, $p$-rational for all $p \geq 2$ (Angelakis–Stevenhagen study on the concept of “minimal absolute abelian Galois group”) which may enlighten a conjecture of $p$-rationality (Hajir–Maire) giving large Iwasawa $\mu$-invariants of some uniform pro-$p$-groups. All programs (in “verbatim”) can be used by the reader by simply copied and pasted.

Résumé. — (Sur la $p$-rationalité des corps de nombres. Applications – Programmes PARI/GP) Soit $K$ un corps de nombres. Nous montrons que son corps de classes de rayon modulo $p^2$ (resp. $8$) si $p > 2$ (resp. $p = 2$) caractérise sa $p$-rationalité. Puis nous donnons deux programmes PARI (Sections 3.1, 3.2) très courts et rapides testant si $K$ (défini par un polynôme irréductible unitaire) est $p$-rationnel ou non. Pour les corps quadratiques nous vérifions certaines densités de corps 3-rationnels en relation avec celles de Cohen–Lenstra–Martinet et nous analysons la conjecture de Greenberg sur l’existence de corps $p$-rationnels de groupes de Galois $(\mathbb{Z}/2\mathbb{Z})^t$ nécessaires pour la construction de certaines représentations galoisiennes d’image ouverte. Nous donnons des exemples pour $p = 3$, $t = 5$ et $t = 6$ (Sections 5.1, 5.2) et illustrons d’autres approches (Pitoun–Varescon, Barbulescu–Ray). Nous concluons sur l’existence de corps quadratiques imaginaires $p$-rationnels pour tout $p \geq 2$ (étude de Angelakis–Stevenhagen sur le concept de “groupe de Galois abélien absolu minimal”) qui peut éclairer une conjecture de $p$-rationalité (Hajir–Maire) donnant de grands invariants $\mu$ d’Iwasawa relatifs à certains pro-$p$-groupes uniformes. Tous les programmes (en “verbatim”) sont utilisables par le lecteur par simple copié-collé.

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1. Definition and properties of $p$-rationality

Let $K$ be a number field and let $p \geq 2$ be a fixed prime number. We denote by $\mathcal{C}_K$ the $p$-class group of $K$ in the ordinary sense and by $E_K$ the group of $p$-principal global units $\varepsilon \equiv 1 \pmod{\prod_{p|p} p}$ of $K$.

Let us describe the diagram of the so called abelian $p$-ramification theory (from [10, §III.2(c), Fig. 2.2], [13, §3]), in which $\widetilde{K}$ is the compositum of the $\mathbb{Z}_p$-extensions of $K$, $H_K$ the $p$-Hilbert class field, $H_K^{\text{pr}}$ the maximal abelian $p$-ramified (i.e., unramified outside $p$) pro-$p$-extension of $K$, then $\text{Gal}(H_K^{\text{bp}}/\widetilde{K})$ is the Bertrandias–Payan module [20, §2, Diagramme 4].

See [3] and [20, §2, Diagram 2] for a related context with logarithmic class groups. Let $U_K := \bigoplus_{p|p} U^1_p$ be the $\mathbb{Z}_p$-module of $p$-principal local units of $K$, where each $U^1_p := \{ u \in K_p^\times, u \equiv 1 \pmod{\mathfrak{p}} \}$ is the group of $\mathfrak{p}$-principal units of the completion $K_p$ of $K$ at $\mathfrak{p}$, where $\mathfrak{p}$ is the maximal ideal of the ring of integers of $K_p$.

For any field $k$, let $\mu_k$ be the $p$-group of roots of unity of $k$. Then put $W_K := \text{tor}_{\mathbb{Z}_p}(U_K) = \bigoplus_{\mathfrak{p}|p} \mu_{K_p}$ and $W_K := W_K/\mu_K$.

Let $E_K$ be the closure in $U_K$ of the diagonal image of $E_K$; this gives $\text{Gal}(H_K^{\text{pr}}/K) \simeq U_K/E_K$ in the diagram:

\[ \xymatrix{ \widetilde{K} & \text{Tor}_{\mathbb{Z}_p}(\text{Gal}(H_K^{\text{pr}}/K)) = \text{Gal}(H_K^{\text{pr}}/\widetilde{K}); } \]

in the viewpoint of Artin symbol, $T_K$ is the kernel of the “logarithmic” map:

\[ A_K \xrightarrow{\text{Art}^{-1}} I_K/P_{K,\infty} \xrightarrow{\text{Log}} \mathbb{Z}_p \text{Log}(I_K) \subseteq \left( \bigoplus_{\mathfrak{p}|p} K_p \right)/\mathbb{Q}_p \text{Log}(E_K), \]

where $I_K := I_K \otimes \mathbb{Z}_p$, $I_K$ being the group of prime to $p$ ideals of $K$, and $P_{K,\infty}$ the group of infinitesimal principal ideals; log is the $p$-adic logarithm, and $\text{Log}(\alpha) := \frac{1}{m} \log(\alpha)$.
(mod \( \mathbb{Q}_p \log(E_K) \)) for any relation in \( I_K \) of the form:

\[
a^m = (\alpha), \quad m \in \mathbb{Z} \setminus \{0\}, \quad \alpha \in K^\times.
\]

Let \( \mathcal{O}_K^\infty \) be the subgroup of \( \mathcal{O}_K \) corresponding, by class field theory, to \( \text{Gal}(H_K/\overline{K} \cap H_K) \).

We have, under the Leopoldt conjecture, the exact sequence defining \( \mathcal{R}_K \) ([10, Lem. III.4.2.4] or [13, Lem. 3.1 & §5]):

\[
1 \to \mathcal{W}_K \to \text{tor}_{\mathcal{Z}_p}(U_K/E_K) \xrightarrow{\log} \text{tor}_{\mathcal{Z}_p}(\log(U_K)/\log(E_K)) =: \mathcal{R}_K \to 0.
\]

The group \( \mathcal{R}_K \) is called the normalized \( p \)-adic regulator of \( K \) and makes sense for any number field.

**Definition 1.1.** — The field \( K \) is said to be \( p \)-rational if the Leopoldt conjecture is satisfied for \( p \) in \( K \) and if the torsion group \( T_K \) is trivial.

**Theorem 1.2** ([16, Thm. & Déf. 4.1] or [10, Thm. IV.3.5]). — For a number field \( K \), each of the following properties is equivalent to its \( p \)-rationality (where \( 2r_2 \) is the number of complex embeddings of \( K \)):

1. \( \mathcal{A}_K := \text{Gal}(H_K^{pr}/K) \simeq \mathbb{Z}_p^{2r_2+1} \),

2. the Galois group \( \mathcal{G}_K \) of the maximal \( p \)-ramified \( \text{pro-}p \)-extension of \( K \) is a free \( \text{pro-}p \)-group on \( r_2+1 \) generators (i.e., \( H^2(\mathcal{G}_K, \mathbb{Z}/p\mathbb{Z}) = 1 \)),

3. we have the following alternative:
   - either \( \mu_p \subset K \), the set of \( p \)-places of \( K \) is a singleton \( \{p\} \), and \( p \) generates the \( p \)-class group of \( K \) (in the restricted sense for \( p = 2 \)),
   - or \( \mu_p \not\subset K \) (whence \( p \neq 2 \)), no prime ideal \( \mathfrak{p} \) of \( K \) is totally split in \( K(\mu_p)/K \) and the \( \omega \)-components of the \( p \)-classes of the \( \mathfrak{P} \) \( \mathfrak{p} \) in \( K(\mu_p) \) generate the \( \omega \)-component of the \( p \)-class group of \( K(\mu_p) \), where \( \omega \) is the Teichmüller character.

We can give, for \( p = 2 \) and \( p = 3 \), more elaborate statements as follows:

**Example 1.3.** — From [9, §III.2, Corollary to Thm. 2] using properties of the “regular kernel” of the \( \text{rk}_2(K) \) of a number field, or [10, Ex. IV.3.5.1] from properties of the groups \( T_K \), we can characterize the \( 2 \)-rationality of 2-extensions of \( \mathbb{Q} \), independently of (iii):

The set of abelian 2-rational 2-extensions of \( \mathbb{Q} \) are all the subfields of the compositum \( \mathbb{Q}(\mu_{2\infty}) \):

\[
\mathbb{Q}(\mu_{2\infty}) \cdot \mathbb{Q}\left(\sqrt[\ell]{a-b}/2\right), \quad \ell \equiv a^2 + b^2 \equiv 5 \pmod{8} \text{ prime, } a \text{ odd.}
\]

For quadratic fields this gives, for any \( \ell \equiv \pm 3 \pmod{8} \)

\[
K \in \{\mathbb{Q}(\sqrt{-1}), \mathbb{Q}(\sqrt{2}), \mathbb{Q}(\sqrt{-2}), \mathbb{Q}(\sqrt{\ell}), \mathbb{Q}(\sqrt{2\ell}), \mathbb{Q}(\sqrt{-2\ell})\}.
\]

**Example 1.4.** — In the same way, the set of abelian 3-rational 3-extensions of \( \mathbb{Q} \) are all the subfields of the compositum of any cubic field of prime conductor \( \ell \equiv \frac{a^2 + 27b^2}{4} \equiv 4 \text{ or } 7 \pmod{9} \) (for which a defining monic polynomial is \( x^3 + x^2 - \frac{\ell-1}{3} x - \frac{\ell(a+3)-1}{27}, a \equiv 1 \pmod{3} \)), with the cyclotomic \( \mathbb{Z}_3 \)-extension.
Example 1.5. — Consider the prime $p = 3$ and a quadratic field $K = \mathbb{Q}(\sqrt{3})$, $d \in \mathbb{Z}$, $K \neq \mathbb{Q}(\sqrt{-3})$; in this case the $\omega$-component of the 3-class group of $K(\mu_3) = K(\sqrt{-3})$ is isomorphic to the 3-class group of the mirror field $K^* := \mathbb{Q}(\sqrt{-3}d)$. Moreover the 3-class of $p \mid 3$ in $\mathbb{Q}(\sqrt{-3}d)$ is trivial since 3 is ramified or inert in this extension under the non-splitting assumption in $K(\mu_3)/K$. Thus in that case, the 3-rationality of $K$ is equivalent to fulfill the following two conditions for $K \neq \mathbb{Q}(\sqrt{-3})$:

(i) The 3-class group of $K^* = \mathbb{Q}(\sqrt{-3}d)$ is trivial,

(ii) we have $d \equiv \pm 1 \pmod{3}$ (i.e., ramification of 3 in $K^*$) or $d \equiv 3 \pmod{9}$ (i.e., inertia of 3 in $K^*$).

If $d \equiv -3 \pmod{9}$, the prime ideal above 3 in $K$ splits in $K(\sqrt{-3})$ so that the non-3-rationality of $K$ comes from the factor $\bigoplus_{p \mid p} \mu_{K_p}/\mu_K \simeq \mathbb{Z}/3\mathbb{Z}$ for the unique $p \mid 3$ in $K$.

Remarks 1.6. — (a) Under Leopoldt’s conjecture, the transfer homomorphisms $T_k \to T_K$ are injective in any extension $K/k$ of number fields [10, Thm. IV.2.1]; so if $K$ is $p$-rational, all the subfields of $K$ are $p$-rational. If $[K : \mathbb{Q}] \neq 0 \pmod{p}$, the norms $N_{K/k} : T_K \to T_k$ (which correspond to the restrictions $T_K \to T_k$ by class field theory) are surjective for all $k \subseteq K$. When $K/\mathbb{Q}$ is Galois and $[K : \mathbb{Q}] \neq 0 \pmod{p}$, the reciprocal about the $p$-rationalities of subfields of $K$ is true for some Galois groups $G := \text{Gal}(K/\mathbb{Q})$ and some families of subfields.

This occurs for instance when $K/\mathbb{Q}$ is abelian with the family of all maximal cyclic subfields of $K$: indeed, as $[K : \mathbb{Q}] \neq 0 \pmod{p}$, $T_K \simeq \bigoplus \chi T_K^\chi$, where $\chi$ runs through the set of rational characters of $G$, $e_\chi$ being the corresponding idempotent; then $T_K^\chi$ is isomorphic to a submodule of $T_k^\chi$ where $k_\chi$ (cyclic) is the subfield of $K$ fixed by the kernel of $\chi$.

For a compositum $K$ of quadratic fields, this means that, for $p > 2$, $K$ is $p$-rational if and only if all the quadratic subfields of $K$ are $p$-rational.

(b) When $K$ is a $p$-extension of a $p$-rational field $k$, $K$ is $p$-rational if and only if the extension $K/k$ is $p$-primitively ramified. This notion, defined first in [9, Chap. III, §1 & §2] form our Crelle’s papers on $p$-ramification and in [16, §1], contains the case of $p$-ramification and some other explicit cases as in Examples 1.3 and 1.4; this notion has been extensively applied in [10, Thm. IV.3.3, Def. IV.3.4], [20, 21, 23, 24].

(c) In [17], abelian $\ell$-extensions ($\ell \neq p$ prime) are used for applications to continuous Galois representations $\text{Gal}(\overline{\mathbb{Q}}/\mathbb{Q}) \to \text{GL}_n(\mathbb{Z}_p)$ with open image for which one needs the condition (ii) of Theorem 1.2 (i.e., the $p$-rationality), and where some properties given in the above references are proved again.

(d) We have conjectured in [12] that $K$ is $p$-rational for all $p \gg 0$, but in practical applications one works with small primes; so, care has been taken to consider also the case $p = 2$ in the programs. We ignore what kind of heuristics (in the meaning of many works such as [4, 5, 6, 8, 27] on class groups, Tate–Sfararevich groups, . . .) are relevant for the $T_K$ when $p$ varies. This should be very interesting since the $T_K$ mix classes and units and since the dual of $T_K$ is $H^2(G_K, \mathbb{Z}_p)$. 

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From the general schema, $\mathcal{T}_K = 1$ if and only if the three invariants $W_K$, $R_K$ and $\mathcal{O}_K^\infty$, are trivial. Thus, in some cases, it may be possible to test each of these trivialities, depending on the knowledge of the field $K$; for instance, assuming the $p$-class group trivial and $p$ unramified, the computation of $W_K$ is purely local and that of the normalized $p$-adic regulator $\mathcal{R}_K$, closely related to the classical $p$-adic regulator, may be given in a specific program since it is the most unpredictable invariant. But a field given by means of a polynomial $P$ may be more mysterious regarding these three factors.

2. General theoretical test of $p$-rationality

2.1. Test using a suitable ray class group. — In [28] and [29, Thm. 3.11 & Cor. 4.1], are given analogous methods for the general computation of the structure of $\mathcal{T}_K$, but here we need only to characterize the triviality (or not) of $\mathcal{T}_K$ in the relation:

$$\mathcal{A}_K := \text{Gal}(H^p_K/K) \simeq \mathbb{Z}_p^r \times \mathcal{T}_K,$$

where $r = r_2 + 1$, $2r_2$ being the number of complex embeddings of $K$. As $\mathcal{T}_K$ is a direct factor in $\mathcal{A}_K$, the structure of the whole Galois group $\mathcal{A}_K$ may be analyzed at a finite step by means of the Galois group of a suitable ray class field $K(p^n)$ of modulus $(p^n)$. Since PARI gives the structure of ray class groups $\mathcal{O}_K(p^n) := \text{Gal}(K(p^n)/K)$, the test of $p$-rationality is obtained for $n$ large enough as follows: if $\mathcal{O}_K(p^n)$ has a $p$-rank such that:

$$\text{rk}_p(\mathcal{O}_K(p^n)) \geq r + 1,$$

then $K$ is not $p$-rational since Gal($\bar{K}/K$) has $p$-rank $r$. The minimal $n_0$ needed for the test is given as a consequence of the following general result:

**Theorem 2.1.** — For any $p | p$ in $K$ and any $j \geq 1$, let $U^j_p$ be the group of local units $1 + \mathfrak{p}^j$, where $\mathfrak{p}$ is the maximal ideal of the ring of integers of $K_p$. For a modulus of the form $(p^n)$, $n \geq 0$, let $\mathcal{A}_K(p^n)$ be the corresponding ray class group. Then for $m \geq n \geq 0$, we have the inequalities:

$$0 \leq \text{rk}_p(\mathcal{O}_K(p^m)) - \text{rk}_p(\mathcal{O}_K(p^n)) \leq \sum_{p | p} \text{rk}_p((U^1_p)^p U_p^{n-ep} / (U^1_p)^p U_p^{m-ep}),$$

where $e_p$ is the ramification index of $p$ in $K/\mathbb{Q}$.

*Proof.* — From [10, Thm. I.4.5 & Cor. I.4.5.4] taking for “$T$” the set of $p$-places and for “$S$” the set of real infinite places (which gives the ordinary sense). □

**Corollary 2.2.** — We have $\text{rk}_p(\mathcal{O}_K(p^m)) = \text{rk}_p(\mathcal{O}_K(p^n)) = \text{rk}_p(\mathcal{A}_K)$ for all $m \geq n \geq n_0$, where $n_0 = 3$ for $p = 2$ and $n_0 = 2$ for $p > 2$. Thus $K$ is $p$-rational if and only if $\text{rk}_p(\mathcal{O}_K(p^{n_0})) = r$, where $r = r_2 + 1$.

*Proof.* — It is sufficient to get, for some fixed $n \geq 0$:

$$(U^1_p)^p U_p^{n-ep} = (U^1_p)^p,$$

hence $U_p^{n-ep} \subseteq (U^1_p)^p$ for all $p | p$; indeed, we then have:

$$\text{rk}_p(\mathcal{O}_K(p^n)) = \text{rk}_p(\mathcal{O}_K(p^m)) = r + \text{rk}_p(\mathcal{T}_K) \text{ as } m \to \infty,$$
giving \( \text{rk}_p(\mathcal{O}_K(p^n)) = r + \text{rk}_p(\mathcal{T}_K) \) for such \( n \). The condition \( U_p^{n\cdot e_p} \subseteq (U_p^1)^p \) is fulfilled as soon as \( n \cdot e_p > \frac{p^{e_p}}{p-1} \), hence:

\[
\frac{n}{p-1} > \frac{p^{e_p}}{p-1}.
\]

(see [7, Chap. I, §5.8, Cor. 2] or [31, Prop. 5.7]; a fact also used in [18, Prop. 1.13]), whence the value of \( n_0 \); furthermore, \( \mathcal{O}_K(p^{n_0}) \) gives the exact \( p \)-rank of \( \mathcal{T}_K \). \[\Box\]

2.2. Basic invariants of \( K \) with PARI [30]. — All the programing parts of the paper are based on few PARI instructions for class field theory and any reader can use them without extensive knowledge of PARI. The reader wishing to test only \( p \)-rationalities may go directly to Subsections 3.1 and 3.2. The following examples will be given with the polynomial

\[
P = x^3 - 5x + 3
\]

defining \( K \) (recall that for PARI, \( P \) must be monic and in \( \mathbb{Z}[x] \)), for which one gives the classical information (test of irreducibility, Galois group of the Galois closure of \( K \), discriminant of \( K \)) which are the following, with the PARI responses:

\[
\text{polisirreducible}(x^3-5*x+3)
\]
\[
1
\]
\[
\text{polgalois}(x^3-5*x+3)
\]
\[
[6,-1,1,"S3"]
\]
\[
\text{factor(nfdisc(x^3-5*x+3))}
\]
\[
[257 1]
\]

showing that \( P \) is irreducible, that the Galois closure of \( K \) is the diedral group of order 6, and that the discriminant of \( K \) is the prime 257.

Then \( K \) is precised by the signature \([r_1, r_2]\), the structure of the whole class group and the fundamental units.

\[
\{P=x^3-5*x+3;K=bnfinit(P,1);C7=component(K,7);C8=component(K,8);Sign=component(C7,2);
\]
\[
\text{print("Signature of } K: ",Sign);print("Structure of the class group: ",component(C8,1));
\]
\[
\text{print("Fundamental system of units: ",component(C8,5"," regulator=",component(C8,2))")}
\]
\[
[3, 0], [1, [], []], [x-1, x^2+2*x-2], \text{ regulator}=1.9745938707807071638559992864525645139
\]

giving a totally real field, a trivial class group and the two fundamental units. From \( K = bnfinit(P,1) \) and \( C8 = component(K,8) \), the regulator of \( K \) is given by \( component(C8,2) \).

The next program gives, for information, the decomposition of some primes \( p \):

\[
\{P=x^3-5*x+3;K=bnfinit(P,1);forprime(p=2,13,print(p," ",idealfactor(K,p)))\}
\]
\[
2 \text{ Mat([[2,[2,0,0]~,-1,3,1],[1])}}
\]
\[
3 \text{ [[3,[0,0,1]~,1,1,1]-1,1,1,1]-1,1,2,[0,0,1]-1,1]}\]
\[
5 \text{ [[5,[2,0,1]~,1,1,2,[2,1,2]-1,1,2,[2,0,1]-1,1]}\]
\[
7 \text{ [[7,[1,0,1]~,1,1,2,[1,1,2]-1,1,2,[1,0,1]-1,1]}\]
\[
11 \text{ Mat([[11,[11,0,0]~,1,3,1],[1]])}
\]
\[
13 \text{ Mat([[13,[13,0,0]~,1,3,1],[1]])}
\]

showing that 2, 11, 13 are inert, that 3, 5, 7 split into two prime ideals with residue degrees 1 and 2, respectively. Taking \( p = 257 \), one obtains:

\[
257 \text{ [[257,[-101,0,1]~,1,1,[-81,1,100]-1,1]}\]
\[
[257,[-78,0,1]~,2,1,[-86,1,77]-1,2]}
\]
which splits into $p_1 \cdot p_2^2$.

To obtain a polynomial from a compositum of known fields (e.g., quadratic fields) one uses by induction the instruction `polcompositum`:

```plaintext
{P1=x^2-2;P2=x^2+5;P3=x^2-7;P=polcompositum(P1,P2);P=component(P,1);
P=polcompositum(P,P3);P=component(P,1);print(P)}
```

$x^8-16x^6+344x^4+2240x^2+19600$

The instruction giving the structure of $C_\ell K(p^n)$ is the following (we compute the structure of the ray class groups with modulus $p^n$, up to $n = 5$, to see the stabilization of the $p$-ranks; this would give, for $n$ large enough, the group invariants of $T_K$, as is done in [28, 29]):

```plaintext
{K=bnfinit(x^3-5*x+3,1);p=2;for(n=0,5,Hpn=bnrinit(K,p^n);print(n," ",component(Hpn,5)))}
```

```
0 [1,[1]] 1 [1,[1]] 2 [2,[2]] 3 [4,[2,2]] 4 [8,[4,2]] 5 [16,[8,2]]
```

(where $32896 = 2^7 \cdot 257$, $8454272 = 2^7 \cdot 257^2$, $2172747904 = 2^7 \cdot 257^3$, ...). Thus $K$ is $p$-rational for $p = 3$ and 257, but not for $p = 2$.

Now we give the case of the first irregular prime $p = 37$ for which we know that the $p$th cyclotomic field is not $p$-rational (indeed, $T_K = 1$ is equivalent to $C_\ell K = 1$ for the $p$th cyclotomic fields [16, Thm. & Déf. 2.1]). So we must see that the $p$-ranks are equal to $19 + 1$, at least for $n \geq 2$:

```plaintext
{p=37;K=bnfinit(polcyclo(p),1);for(n=0,5,Hpn=bnrinit(K,p^n);print(n," ",component(Hpn,5)))}
```

```
0 [37,[37]] 1 [6249190990842127748277129373,[1369,37,37,37,37,37,37,37,37,37,37,37,37,37,37,37,37,37,37,37]]
2 [3905399933637779632089821318184819006713655084697379373129,[50653,1369,1369,1369,1369,1369,1369,1369,1369,1369,1369,1369,1369,1369,1369,1369,1369,37,37,37]]
```

where $1369 = 37^2$, $50653 = 37^3$.

### 3. Full general PARI programs testing $p$-rationality

We bring together some instructions given in the previous section and recall that, in the programs, $n = 2$ (resp. 3) if $p \neq 2$ (resp. $p = 2$).

#### 3.1. General program with main invariants and test of $p$-rationality

— The reader has to introduce an irreducible monic polynomial $P \in \mathbb{Z}[x]$ and a prime number $p \geq 2$. For $p = 2$ the $p$-rationality is in the ordinary sense.

```plaintext
{P=x^3-5*x+3;p=2;K=bnfinit(P,1);Sign=component(component(K,7),2);
print("Signature of K: ",Sign);print("Galois group of the Galois closure of K: ",polgalois(P));
print("Discriminant: ",factor(component(component(K,7),3)));
print("Structure of the class group: ",component(component(K,8),1))}
```
print("Fundamental system of units: ",component(component(K,8),5));r=component(Sign,2)+1;
n=2;if(p==2,n=3);print(p,"-rank of the compositum of the Z","_",p,"-extensions: ",r);
Hp=component(component(bnrinit(K,p^n),5),2);L=listcreate;e=component(matsize(Hp),2);
R=0;for(k=1,e,c=component(Hp,e-k+1);if(Mod(c,p)==0,R=R+1;listinsert(L,p^valuation(c,p),1)));
print("Structure of the ray class group mod ",p,"^n: ",L);
if(R>r,print("rk(T)=",R-r," K is not ",p,"-rational"));
if(R==r,print("rk(T)=",R-r," K is ",p,"-rational"))}

(i) With the above data, $K$ is not 2-rational nor 293-rational (up to $p \leq 10^5$).

(ii) The field $K = \mathbb{Q}(\sqrt{-161})$ is not 2-rational (one may prove that the 2-Hilbert class field is linearly disjoint from $\tilde{K}$ [10, Ex. III.6.7]).

(iii) The field $K = \mathbb{Q}(\sqrt{-69})$ is not 3-rational (comes from $\mathcal{R}_K \equiv 0 \pmod{3}$).

(iv) The quartic cyclic fields $K$ defined by $P = x^4 + 5x^2 + 5$ (conductor 5) and by $P = x^4 + 13x^2 + 13$ (conductor 13) are 2-rational (see Example 1.3).

3.2. Test of $p$-rationality (simplified programs). — Since some parts of the first program are useless and some computations intricate (e.g., Galois groups in large degrees), one may use the following simplified program to test only the $p$-rationality.

We test the 3-rationality of $K = \mathbb{Q}(\sqrt{-1}, \sqrt{2}, \sqrt{5}, \sqrt{11}, \sqrt{97})$ given in [17] ($P$ is computed from the instruction \texttt{polcompositum}; the program takes 19 min, 26.663 ms:

Programme I (define the polynomial P and the prime p):

\begin{verbatim}
{P=x^32-1824*x^30+1504544*x^28-743642240*x^26+246039201472*x^24-57656224594432*x^22
+9874427075761664*x^20-12570373661975865344*x^18+119781806181353182720*x^16
-853433587893228562944*x^14+450656884816602311041024*x^12
-1733017965267833219399680*x^10+471547188605910876106571776*x^8
-8678487487392950825437910464*x^6+100678473735628844348283158528*x^4
-658128522558749792210233894672*x^2+199591843513957384065800304696;
K=bnfinit(P,1);p=3;n=2;if(p==2,n=3);Kpn=bnrinit(K,p^n);S=component(component(Kpn,1),7);
r=component(component(S,2),2)+1;
print(p,"-rank of the compositum of the Z","_",p,"-extensions: ",r);
Hp=component(component(Kpn,5),2);L=listcreate;e=component(matsize(Hp),2);R=0;
for(k=1,e,c=component(Hp,e-k+1);if(Mod(c,p)==0,R=R+1;listinsert(L,p^valuation(c,p),1)));
print("Structure of the ",p,"-ray class group: ",L);
if(R>r,print("rk(T)=",R-r," K is not ",p,"-rational"));
if(R==r,print("rk(T)=",R-r," K is ",p,"-rational"))}
\end{verbatim}

3-rank of the compositum of the Z_3-extensions: 17
Structure of the 3-ray class group: List([3,3,3,3,3,3,3,3,3,3,3,3,3,3,9,9,9])
K is 3-rational

If one wishes to test the $p$-rationality of $K$ for $p$ varying in an interval $[b, B]$, it is necessary to compute first the data \texttt{bnfinit}(P, 1) which is independent of $p$ and takes lots of time. Then the tests for $p$-rationalities are very fast. This gives the following writing where we give the $p$-structure of $\mathcal{O}_K(p^{n_0})$ up to $p \leq 100$, only for the non-$p$-rational cases:

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Programme II (define $P$ and the interval $[b,B]$ of primes $p$):

\[ P = x^{32} - 1824x^{30} + 1504544x^{28} - 743642240x^{26} + 246039201472x^{24} - 57656224594432x^{22} + 9874427075761664x^{20} - 1257037661975865344x^{18} + 119781806181353182720x^{16} - 853433587893222862944x^{14} + 1450658848166023111041024x^{12} - 173301719526783321999680x^{10} + 10471547188605910876106571776x^8 - 8678484783929508254539710464x^6 + 100678434773562884438283158528x^4 - 65128522558747992210233884672x^2 + 1995918433518957384605860304896; \]

\[ K = \text{bnfinit}(P,1); b = 2; B = 100; r = \text{component(component(component(K,7),2),2)} + 1; \]

\[ \text{print}("p-rank of the compositum of the $\mathbb{Z}_p$-extensions: ", r); \]

\[ \text{forprime}(p = b, B, n = 2; \text{if}(p = 2, n = 3); \text{Kpn} = \text{bnrinit}(K, p^n); Hpn = \text{component(component(Kpn,5),2)}; e = \text{component(matsize(Hpn),2)}; R = 0; \text{for}(k = 1, e, c = \text{component(Hpn,e-k+1)}; \text{if}(\text{Mod}(c, p) == 0, R = R + 1; \text{listinsert}(L, p^\text{valuation(c,p)}, 1))); \]

\[ \text{print}("Structure of the ", p, "-ray class group: ", L); \]

\[ \text{if}(R > r, \text{print}("rk(T) = \text{R-r, K is not } p\text{-rational}"); \]

\[ \text{if}(R == r, \text{print}("rk(T) = \text{R-r, K is } p\text{-rational})\}); \]

The $p$-rationality holds for $3, 5, 23, 37, 47, 53, 59, 61, 67, 71, 79, 83, 89, 97$ and we find that $K$ is not $p$-rational up to $10^5$ for the primes:

\[ p \in \{2, 7, 11, 13, 17, 19, 29, 31, 43, 73, 163, 191, 263, 409, 571, 643, 1049, 2671, 3331, 3917, 6673, 8941, 28477, 36899, 39139, 85601, 99149, 134339, 203393, 231901, 283979, 353711, 363719\}. \]

The above cases of non-$p$-rationality are numerous, because of the important number of maximal cyclic subfields of $K$, and are essentially due to some units; for instance, for the unit $\varepsilon = 1 + \sqrt{2} \in \mathcal{O}_K$ and $p = 31$, we get

\[ \varepsilon^{30} = 152139002499 + 107578520350 \sqrt{2} \equiv 1 \pmod{31^2}, \]

which means

\[ \mathcal{R}_K = \frac{1}{31} \log(\varepsilon) \equiv 0 \pmod{31}. \]
For the polynomial $P = x^3 + 2$, the $p$-rationality holds for $2 \leq p \leq 10^7$.

\begin{verbatim}
{P=x^3+2;K=bnfinit(P,1);b=2;B=10^7;r=component(component(component(K,7),2),2)+1;
 print("p-rank of the compositum of the Z_p-extensions: ",r);
 forprime(p=b,B,n=2;if(p==2,n=3); Kpn=bnrinit(K,p^n);Hpn=component(component(Kpn,5),2);
e=component(matsize(Hpn),2);R=0;for(k=1,e,c=component(Hpn,e-k+1);
 if(Mod(c,p)==0,R=R+1));if(R>r,print("rk(T)="",R-r," K is not ",p,"-rational"))}
\end{verbatim}

4. Heuristics on Greenberg's conjecture (with $p = 3$)

4.1. Generalities. — A conjecture, in relation with the construction of continuous Galois representations $\text{Gal}(\overline{\mathbb{Q}}/\mathbb{Q}) \to \text{GL}_n(\mathbb{Z}_p)$ with open image, is the following, stated in the case of a compositum of quadratic fields [17, Conj. 4.2.1]:

**Conjecture 4.1.** — For any odd prime $p$ and for any $t \geq 1$ there exists a $p$-rational field $K$ such that $\text{Gal}(K/\mathbb{Q}) \simeq (\mathbb{Z}/2\mathbb{Z})^t$.

For the link between $n$ and $t$ and more information, see [17, Prop. 6.1.1 & 6.2.2]. For simplicity, we shall discuss this conjecture for $p = 3$ (for other cases, see [2, Table 1]); then the 3-rationality of a compositum of $t$ quadratic fields is equivalent to the following condition (from Example 1.5):

For all the quadratic subfields $k = \mathbb{Q}(\sqrt{d}) \neq \mathbb{Q}(\sqrt{-3})$ of $K$, the 3-class group of the mirror field $k^* := \mathbb{Q}(\sqrt{-3 \cdot d})$ is trivial and 3 does not split in $k^*/\mathbb{Q}$.

This needs $2^t - 1$ conditions of 3-rationality (note that $\mathbb{Q}(\sqrt{-3})$ is $p$-rational for all $p$).

4.2. Technical conditions. — The case $t = 1$ is clear (see Theorem 1.2(iii)) and gives infinitely many 3-rational fields if we refer to classical heuristics [4, 5]. When $t \geq 3$ we must assume that $\mathbb{Q}(\sqrt{-3})$ is not contained in $K$, otherwise, if $K_0$ is the inertia field of 3 in $K/\mathbb{Q}$, then $[K : K_0] = 2$, $[K_0 : \mathbb{Q}] \geq 4$, and necessarily 3 splits in part in $K_0/\mathbb{Q}$ (the factor $\mathcal{W}_K$ is non-trivial).

For the biquadratic field $\mathbb{Q}(\sqrt{d}, \sqrt{-3})$, $d \neq 0 (\text{mod } 3)$, the 3-rationality holds if and only if $d \equiv -1 (\text{mod } 3)$ and the 3-class group of the imaginary field $\mathbb{Q}(\sqrt{d})$ or $\mathbb{Q}(\sqrt{-3 \cdot d})$ is trivial (using Scholz’s theorem). In the sequel, we shall assume that $K$ does not contain $\mathbb{Q}(\sqrt{-3})$ and that $t \geq 3$.

Let $K = \mathbb{Q}(\sqrt{d_1}, \ldots, \sqrt{d_t})$ be such that $\text{Gal}(K/\mathbb{Q}) \simeq (\mathbb{Z}/2\mathbb{Z})^t$, $t \geq 3$. We denote by $k = \mathbb{Q}(\sqrt{d})$ any quadratic subfield of $K$ and by $k^*$ the “mirror field” $\mathbb{Q}(\sqrt{-3 \cdot d})$. We then have the obvious lemma:

**Lemma 4.2.** — The conditions of non-splitting of 3 in all the extensions $k^*/\mathbb{Q}$, $k = \mathbb{Q}(\sqrt{d}) \subseteq K$, are satisfied if and only if for all the integers $d$ we have $d \neq 0 (\text{mod } 3)$ or $d \equiv 3 (\text{mod } 9)$.

**Corollary 4.3.** — (i) If 3 is unramified in $K/\mathbb{Q}$, then $K = \mathbb{Q}(\sqrt{d_1}, \ldots, \sqrt{d_t})$ with $d_i \equiv \pm 1 (\text{mod } 3)$, for $i = 1, \ldots, t$.

(ii) If 3 is ramified in $K/\mathbb{Q}$ then $K$ is a direct compositum of the form $K_0 \mathbb{Q}(\sqrt{3d_1})$, where 3 is unramified in $K_0$ and $d_i \neq 0 (\text{mod } 3)$, whence $K = \mathbb{Q}(\sqrt{d_1}, \ldots, \sqrt{d_{t-1}}, \sqrt{3d_t})$ with $d_i \equiv 1 (\text{mod } 3)$ for $i = 1, \ldots, t$. 


Case (ii) comes from the fact that for any $d \in \langle d_1, \ldots, d_{t-1} \rangle \cdot \mathbb{Q}^\times$, $d \not\equiv 0 \pmod{3}$, the consideration of the subfield $k = \mathbb{Q}(\sqrt{3d_1d})$ needs, for $k^* = \mathbb{Q}(\sqrt{-d_1d})$, the condition $d_1d \equiv 1 \pmod{3}$, whence the hypothesis as soon as $t \geq 3$. So whatever the form of $K$, the results depend on heuristics on the 3-class groups of the $2^t - 1$ fields $k^*$ when random integers $d_i$ are given with the above conditions.

A first heuristic is to assume that a 3-class group does not depend on the above assumption of decomposition of the prime 3; this is natural since only genera theory (i.e., when $p = 2$) is concerned with such problem. Of course, all the $2^t - 1$ integers $d$ are not random, but the classical studies of repartition of class groups show that the two phenomena (an integer $d$ and a 3-class group) are independent.

4.3. Densities of 3-rational quadratic fields. — We give now estimations of densities of 3-rational quadratic fields $K = \mathbb{Q}(\sqrt{d})$.

There are two algorithms for this:

- The general Program I of Section 3.2. It is easy to see that Program I takes the same time for real or imaginary fields.

- The characterization given by Example 1.5.

It is clear that the characterization using the computation of class numbers of the mirror fields $K^*$ is faster for real $K$. We shall compare with the heuristics of Cohen–Lenstra–Martinet. So we obtain the following programs in which $N$ (resp. $N_3$) is the number of squarefree integers $d$ (resp. 3 of 3-rational fields $\mathbb{Q}(\sqrt{d})$ in the interval:

4.3.1. Real case for $K$. — The mirror field of $K = \mathbb{Q}(\sqrt{d})$ is $K^* = \mathbb{Q}(\sqrt{-3d})$ and we must have $d \equiv 3 \pmod{9}$ when $3 \mid d$, otherwise 3 splits in $K(\mu_3)/K$ and $\mathcal{W}_K \neq 1$.

```plaintext
{N=0;N3=0;for(d=1,10^6,if(core(d)!=d || Mod(d,9)==-3,next);N=N+1;v=valuation(d,3);
D=coredisc(-3^(1-2*v)*d);h=qfbclassno(D);if(Mod(h,3)!=0,N3=N3+1));print(N3," ",N," ",N3/N+0.0)}
N3=315551, N=531938, N3/N=0.59321
```

If we restrict ourselves to integers $d \equiv 3 \pmod{9}$, we obtain $N_3 = 180717$, $N = 303961$ and the proportion 0.59454. With the condition $d \not\equiv 0 \pmod{3}$ (corresponding to the non-ramification of 3 in $K$) we obtain the similar proportion 0.59185.

This is consistent with the heuristics of Cohen–Martinet, about 3-class groups (see [5, §2, 1.1(b)] or [4, §9(b)]), giving the probability 0.439874 for 3 \# $\mathcal{C}_k^*$, whence 0.560126 for the contrary.

4.3.2. Imaginary case for $K$. — The program uses the computation of the ray class group of modulus 9 (see Program I of Section 3.2):

```plaintext
{p=3;n=2;r=2;N=0;N3=0;for(dd=1,10^6,d=-dd;if(core(d)!=d || Mod(d,9)==-3,next);N=N+1;
P=x^2-d;k=bnfinit(P,1);Kpn=bnrinit(K,p^n);Hpn=component(component(Kpn,5),2);
e=component(matsize(Hpn),2);R=0;for(k=1,e,c=component(Hpn,e-k+1);
if(Mod(c,p)==0,R=R+1));if(R==r,N3=N3+1));print(N3," ",N," ",N3/N+0.0)}
N3=462125,N=531934,N3/N=0.868
```

This is in accordance with the probabilities about 3-class groups in the real case giving the probability 0.841 for \# $\mathcal{C}_k^* \not\equiv 0 \pmod{3}$ (see [5, §2, 1.2(b)]).
4.3.3. Conclusion. — Thus, there are approximatively 60% of 3-rational real quadratic fields and around 86% of 3-rational imaginary quadratic fields. So we do not need more precise information, but we must only assume that 3-rational quadratic fields are uniformly distributed whatever the interval of range of the discriminants and that the probabilities are around 0.60 (resp. 0.86) for our reasonnings (in fact, some recent conjectures give a decreasing of the densities, which goes in the good direction). For more precise numerical results and heuristics, see [2, §5], [29, §5] and the very complete work on imaginary quadratic fields [27].

4.4. Analyse of Greenberg’s conjecture. — We denote by $K_t$, $t \geq 1$, a compositum of one of the two forms:

$$K_t = \mathbb{Q}(\sqrt{d_1}, \ldots, \sqrt{d_t}) \quad \text{with} \quad d_i \not\equiv 0 \pmod{3} \quad \text{for all } i,$$

$$K_t = \mathbb{Q}(\sqrt{d_1}, \ldots, \sqrt{d_{t-1}}, \sqrt{3 \cdot d_t}) \quad \text{with} \quad d_i \equiv 1 \pmod{3} \quad \text{for all } i.$$

From the above heuristics, we can say that for $t = 1$ there are reasonably infinitely many such 3-rational $K_1$ with density $P_1$ less than 0.6 or 0.86, respectively.

Now take $t \geq 3$; since $K_t$ is 3-rational if and only if its $2^t - 1$ quadratic subfields are 3-rational, the probability may be assumed to be as follows, under the assumption that all the generators $d_1, \ldots, d_t$ are random under the necessary local conditions of Corollary 4.3:

- If $K_t$ is real, the probability is:

$$P_t \approx 0.60^{2^t-1}$$

(giving $1.33 \cdot 10^{-7}$ for $t = 5$, $1.06 \cdot 10^{-14}$ for $t = 6$, $1.12 \cdot 10^{-227}$ for $t = 10$).

- If $K_t$ is imaginary, we have $2^t - 1$ real quadratic subfields and $2^t - 1$ imaginary ones, so that the probability is:

$$P_t \approx 0.60^{2t-1} \cdot 0.86^{2t-1}$$

(giving $4.2 \cdot 10^{-5}$ for $t = 5$, $1.06 \cdot 10^{-9}$ for $t = 6$, $1.25 \cdot 10^{-147}$ for $t = 10$).

This explains the great difficulties to find numerical examples, for $t > 6$ with $p = 3$, in a reasonable interval $[b, B]$ for $d_1, \ldots, d_t$. Recall the imaginary example with $t = 6$ given in [17, §4.2]: $\mathbb{Q}(\sqrt{-1}, \sqrt{13}, \sqrt{145}, \sqrt{209}, \sqrt{269}, \sqrt{373})$ (we shall give another similar example in Section 5.2).

Naturally, when $p$ increases, it is easier to find examples with larger $t$ but the problem is similar. See [2] for some examples with $p \geq 5$ with quadratic fields (e.g., Table 1 for $\mathbb{Q}(\sqrt{2}, \sqrt{3}, \sqrt{11}, \sqrt{47}, \sqrt{97})$ with $p = 5$) and cubic fields, then [13, 14, 19] for $p$-adic regulators.

In the framework of Borel–Cantelli classical heuristic, the conjecture of Greenberg may be true.

5. Computations for compositum of quadratic fields

5.1. Research of real 3-rational compositum of 5 quadratic fields. — For practical reasons, we write two programs depending on the ramification of 3 in the fields $K = \mathbb{Q}(\sqrt{d_1}, \sqrt{d_2}, \sqrt{d_3}, \sqrt{d_4}, \sqrt{d_5})$. The two programs verify that $\text{Gal}(K/\mathbb{Q}) \simeq (\mathbb{Z}/2\mathbb{Z})^5$ from the data.
5.1.1. Case where $3$ is possibly ramified. — The program computes a list of integers $d > 0$ such that $d \equiv 1 \pmod{3}$ or $d \equiv 3 \pmod{9}$ (see Corollary 4.3) and such that the $\mathbb{Q}(\sqrt{d})$ are $3$-rational (then $3$ is possibly unramified in some solutions $K$, but in that case $d_i \equiv 1 \pmod{3}$ for all $i$).

\[
\{L3=listcreate;N3=0;b=1;B=300;for(d=b,B,if(core(d)!=d||Mod(d,3)==-1||Mod(d,9)==-3,next);
    v=valuation(d,3);D=coredisc(-3^(1-2*v)*d);h=qfbclassno(D);if(Mod(h,3)!=0,N3=N3+1;
    listinsert(L3,d,1)));for(k=1,10^7,a1=random(N3)+1;a2=random(N3)+1;
    a3=random(N3)+1;a4=random(N3)+1;a5=random(N3)+1;di=component(L3,a1);
    d2=component(L3,a2);d3=component(L3,a3);d4=component(L3,a4);d5=component(L3,a5);
    TT=0;for(e1=0,1,for(e2=0,1,for(e3=0,1,for(e4=0,1,for(e5=0,1,
        dd=d1^e1*d2^e2*d3^e3*d4^e4*d5^e5;dd=core(dd);
        if(dd==1 & [e1,e2,e3,e4,e5]!=[0,0,0,0,0],TT=1;break(5))))));
    if(TT==0,T=0;for(e1=0,1,for(e2=0,1,for(e3=0,1,for(e4=0,1,for(e5=0,1,
        dd=d1^e1*d2^e2*d3^e3*d4^e4*d5^e5;dd=core(dd);
        if(Mod(dd,3)!=0,D=coredisc(-3*dd));if(Mod(dd,3)==0,D=coredisc(-dd/3));
        h=qfbclassno(D);if(Mod(h,3)==0,T=1;break(5))))));
    if(T==0,print(d1," ",d2," ",d3," ",d4," ",d5))))
\]

One obtains the following distinct examples:
\[
[d1,d2,d3,d4,d5]=
[118,178,31,46,211],[274,291,66,118,262],[22,193,13,262,163],[37,274,31,211,46],
[31,130,166,129,246],[298,13,7,111,210],[201,157,57,55,219],[255,282,165,298,118],
[19,211,61,166,217],[39,30,129,111,166],[187,246,39,145,31],[166,265,246,219,157],
[55,219,217,102,205],[193,262,163,10,127],[37,61,273,205,21],[255,115,259,193,7],
[31,187,145,246,39]
\]

5.1.2. Case where $3$ is unramified. — In this case there is no condition on the $d_i \neq 0 \pmod{3}$.

\[
\{L3=listcreate;N3=0;b=2;B=300;for(d=b,B,if(core(d)!=d||Mod(d,3)==0,next);
    D=coredisc(-3*d);h=qfbclassno(D);if(Mod(h,3)!=0,N3=N3+1;listinsert(L3,d,1));
    for(k=1,10^7,a1=random(N3)+1;a2=random(N3)+1;
    a3=random(N3)+1;a4=random(N3)+1;a5=random(N3)+1;di=component(L3,a1);
    d2=component(L3,a2);d3=component(L3,a3);d4=component(L3,a4);d5=component(L3,a5);TT=0;
    for(e1=0,1,for(e2=0,1,for(e3=0,1,for(e4=0,1,for(e5=0,1,
        dd=d1^e1*d2^e2*d3^e3*d4^e4*d5^e5;dd=core(dd);
        if(dd==1 & [e1,e2,e3,e4,e5]!=[0,0,0,0,0],TT=1;break(5))))));
    if(TT==0,T=0;for(e1=0,1,for(e2=0,1,for(e3=0,1,for(e4=0,1,for(e5=0,1,
        dd=d1^e1*d2^e2*d3^e3*d4^e4*d5^e5;dd=core(dd);
        D=coredisc(-3*dd));if(Mod(dd,3)==0,D=coredisc(-dd/3));
        h=qfbclassno(D);if(Mod(h,3)==0,T=1;break(5))))));
    if(T==0,print(d1," ",d2," ",d3," ",d4," ",d5))))
\]

One obtains the following examples:
\[
[d1,d2,d3,d4,d5]=
[91,230,209,194,221],[149,335,301,55,31],[145,157,230,209,194],[35,193,301,149,263],
[226,239,130,158,259],[190,259,143,70,290],[266,59,17,10,70],[194,11,283,187,31],
[86,149,170,146,145],[158,259,226,146,47],[146,26,269,166,190],[46,170,38,133,187],
[190,119,97,14,263],[203,227,221,194,143],[239,89,262,53,166],[13,262,193,163,286]
\]

In a larger interval, the examples become more rare since the number of discriminants decrease; between $b = 10^3$ and $B = 10^3 + 350$ we get the solutions (when $3$ can ramify):
\[
[d1,d2,d3,d4,d5]=
[1246,1303,1218,1291,1123],[1177,1003,1309,1173,1054],[1321,1065,1173,1231,1207],
[1156,1326,1111,1105,1093],[1173,1281,1254,1327,1209],[1030,1174,1177,1218,1015]
\]
5.1.3. *Direct verifications.* — To verify, one may compute directly the 3-class number and the 3-adic logarithm of the fundamental unit \( \varepsilon \) of \( \mathbb{Q}(\sqrt{d}) \) for each quadratic subfield of \( K \); the computation of the normalized regulator (using \([13, \text{Prop. } 5.2]\)) is equivalent to that of \( \alpha := \frac{\varepsilon^{q-1}}{\sqrt{d}} \) when 3 is unramified (where \( q = 2 \) or 8), and \( \alpha := \frac{\varepsilon^{q-1}}{\sqrt{d}} \) when 3 \( \nmid d \), \( d \not\equiv -3 \pmod{9} \), and \( \alpha \) must be a 3-adic unit (which can be seen taking its norm):

\[
\{L3=[110,170,161,38,14];d1=\text{component}(L3,1);d2=\text{component}(L3,2);
d3=\text{component}(L3,3);d4=\text{component}(L3,4);d5=\text{component}(L3,5);T=0;
\text{for}(e1=0,1,\text{for}(e2=0,1,\text{for}(e3=0,1,\text{for}(e4=0,1,\text{for}(e5=0,1,
\text{dd}=d1^e1*d2^e2*d3^e3*d4^e4*d5^e5;dd=\text{core}(dd);\text{if}(dd==1,\text{next});
D=\text{coredisc}(dd);h=\text{qfbclassno}(D);\varepsilon=\text{quadunit}(D);q=8;\text{if}(\text{Mod}(dd,3)\neq-1,q=2);
E=\varepsilon^q-1;\text{if}(\text{Mod}(D,3)==-1,\text{No}=\text{norm}(E)/9);\text{if}(\text{Mod}(D,3)==0,\text{No}=\text{norm}(E)/3);
\text{No}=\text{Mod}(\text{No},3);\text{print}(dd, " \text{ mod } 9 \text{ Regulator } \text{ No } \text{ mod } 3 \text{ Regulator } \text{ No })))\}
\]

giving, for \( \mathbb{Q}(\sqrt{110}, \sqrt{170}, \sqrt{161}, \sqrt{38}, \sqrt{14}) \) (computation of \( h \) modulo 9 for information instead of modulo 3):

<table>
<thead>
<tr>
<th>( d )</th>
<th>( h ) mod 9</th>
<th>Regulator</th>
<th>( d )</th>
<th>( h ) mod 9</th>
<th>Regulator</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>Mod(1,9)</td>
<td>Mod(1,3)</td>
<td>38</td>
<td>Mod(1,9)</td>
<td>Mod(1,3)</td>
</tr>
<tr>
<td>133</td>
<td>Mod(1,9)</td>
<td>Mod(2,3)</td>
<td>14630</td>
<td>Mod(8,9)</td>
<td>Mod(1,3)</td>
</tr>
<tr>
<td>161</td>
<td>Mod(1,9)</td>
<td>Mod(1,3)</td>
<td>17710</td>
<td>Mod(8,9)</td>
<td>Mod(2,3)</td>
</tr>
<tr>
<td>46</td>
<td>Mod(1,9)</td>
<td>Mod(2,3)</td>
<td>1265</td>
<td>Mod(2,9)</td>
<td>Mod(1,3)</td>
</tr>
<tr>
<td>6118</td>
<td>Mod(4,9)</td>
<td>Mod(2,3)</td>
<td>168245</td>
<td>Mod(8,9)</td>
<td>Mod(1,3)</td>
</tr>
<tr>
<td>437</td>
<td>Mod(1,9)</td>
<td>Mod(1,3)</td>
<td>48070</td>
<td>Mod(8,9)</td>
<td>Mod(2,3)</td>
</tr>
<tr>
<td>170</td>
<td>Mod(4,9)</td>
<td>Mod(1,3)</td>
<td>187</td>
<td>Mod(2,9)</td>
<td>Mod(2,3)</td>
</tr>
<tr>
<td>595</td>
<td>Mod(4,9)</td>
<td>Mod(2,3)</td>
<td>2618</td>
<td>Mod(4,9)</td>
<td>Mod(1,3)</td>
</tr>
<tr>
<td>1615</td>
<td>Mod(4,9)</td>
<td>Mod(2,3)</td>
<td>7106</td>
<td>Mod(4,9)</td>
<td>Mod(1,3)</td>
</tr>
<tr>
<td>22610</td>
<td>Mod(8,9)</td>
<td>Mod(1,3)</td>
<td>24871</td>
<td>Mod(8,9)</td>
<td>Mod(2,3)</td>
</tr>
<tr>
<td>27370</td>
<td>Mod(7,9)</td>
<td>Mod(2,3)</td>
<td>30107</td>
<td>Mod(8,9)</td>
<td>Mod(1,3)</td>
</tr>
<tr>
<td>1955</td>
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<td>Mod(1,3)</td>
<td>8602</td>
<td>Mod(4,9)</td>
<td>Mod(2,3)</td>
</tr>
<tr>
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<td>Mod(1,3)</td>
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<tr>
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<td>Mod(2,9)</td>
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<td>Mod(8,9)</td>
<td>Mod(1,3)</td>
</tr>
<tr>
<td>110</td>
<td>Mod(2,9)</td>
<td>Mod(1,3)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5.2. *Research of imaginary 3-rational compositum.* — The programs written in Section 5.1 are valid for any interval \([b,B]\) in \( \mathbb{Z} \) and we find, as expected, more solutions that in the real case for \( t = 5 \). Give only an example since the calculations are different for imaginary quadratic subfields. Let \( K = \mathbb{Q}(\sqrt{-1}, \sqrt{7}, \sqrt{10}, \sqrt{13}, \sqrt{37}) \); then a monic polynomial defining \( K \) is:

\[
x^{32}-1056x^{30}+480032x^{28}-124184704x^{26}+20397674176x^{24}-2244202678784x^{22}
+169874210289152x^{20}-8952078632101888x^{18}+329969412292171264x^{16}
-8547361273484173312x^{14}+156988254584490745856x^{12}-2053956312746026343560x^{10}
+1906699132106131953664x^{8}-243537558863823312888096x^{6}+53573917663590716471296x^{4}
-1443775880343438717616128x^{2}+1984177860024815997485056
\]

and the Program I of Section 3.2 confirms the 3-rationality. We also find a new example with \( t = 6 \):

\[ K = \mathbb{Q}(\sqrt{-2}, \sqrt{-5}, \sqrt{7}, \sqrt{17}, \sqrt{-19}, \sqrt{59}) \]

Such examples are very rare and it is probably hopeless to find a numerical example with \( t = 7 \) in a reasonable interval of discriminants.
To verify the 3-rationalities, we use the program of the above subsection, noting that for imaginary quadratic subfields $k$ there is no unit $\varepsilon$ and that its 3-class group may be non-trivial, but in this case the 3-Hilbert class field must be contained in $\tilde{k}$ which gives interesting examples of such phenomena; indeed, this fact is not obvious without explicit knowledge of generators of the 3-classes and we can use directly the Program I of $p$-rationality for each $k$ such that $h \equiv 0 \pmod{3}$.

\begin{verbatim}
{L3=[70,59,-118,-19,17,-14];d1=component(L3,1);d2=component(L3,2);
 d3=component(L3,3);d4=component(L3,4);d5=component(L3,5);d6=component(L3,6);
 T=0;for(e1=0,1,for(e2=0,1,for(e3=0,1,for(e4=0,1,for(e5=0,1,for(e6=0,1,
 dd=d1^e1*d2^e2*d3^e3*d4^e4*d5^e5*d6^e6;dd=core(dd);
 if(dd==1,next);D=coredisc(dd);h=qfbclassno(D);
 if(D>0,eps=quadunit(D);q=8;if(Mod(dd,3)!=-1,q=2);E=eps^q-1;
 if(Mod(D,3)!=0,No=norm(E)/9);if(Mod(D,3)==0,No=norm(E)/3);No=Mod(No,9));
 if(D<0,No=X);print(dd," ",3^valuation(h,3)," ",No))))})

 d h No d h No
-14 1 X -5 1 X
17 1 Mod(1,3) 1190 1 Mod(1,3)
-238 1 X -85 1 X
-19 1 X -1330 3 X
266 1 Mod(1,3) 95 1 Mod(1,3)
-323 1 X -22610 1 X
4522 1 Mod(2,3) 1615 1 Mod(2,3)
-118 3 X -2065 3 X
413 1 Mod(1,3) 590 1 Mod(1,3)
-2006 3 X -35105 1 X
7021 1 Mod(2,3) 10030 1 Mod(2,3)
2242 1 Mod(2,3) 39235 1 Mod(2,3)
-7847 1 X -11210 1 X
38114 1 Mod(1,3) 666995 1 Mod(1,3)
-133399 3 X -190570 1 X
59 1 Mod(1,3) 4130 1 Mod(1,3)
-826 3 X -295 1 X
1003 1 Mod(2,3) 70210 1 Mod(2,3)
-14042 1 X -5015 1 X
-1121 1 X -78470 9 X
15694 1 Mod(2,3) 5605 1 Mod(2,3)
-19057 1 X -1333990 1 X
266798 1 Mod(1,3) 95285 1 Mod(1,3)
-2 1 X -35 1 X
7 1 Mod(2,3) 10 1 Mod(2,3)
-34 1 X -595 1 X
119 1 Mod(1,3) 170 1 Mod(1,3)
38 1 Mod(1,3) 665 1 Mod(1,3)
-133 1 X -190 1 X
646 1 Mod(2,3) 11305 1 Mod(2,3)
-2261 9 X -3230 9 X
70 1 Mod(2,3)

From this table, we deduce that the 3-class group of $K$ is isomorphic to
\[ (\mathbb{Z}/9\mathbb{Z})^3 \times (\mathbb{Z}/3\mathbb{Z})^6 \]
\end{verbatim}
and that the 3-Hilbert class field of \( K \) is contained in the compositum of the 16 independent \( \mathbb{Z}_3 \)-extensions of \( K \) distinct from the cyclotomic one (i.e., the compositum of the 16 “anti-cyclotomic” \( \mathbb{Z}_3 \)-extensions).

6. Number fields \( p \)-rational for all \( p \geq 2 \)

As soon as there exist units of infinite order in \( K \), the \( p \)-rationality is a very difficult question and \textit{a fortiori} the existence of such fields, \( p \)-rational for all \( p \). So it remains to consider the fields such that \( r_1 + r_2 - 1 = 0 \), which characterizes \( K = \mathbb{Q} \) (which is \( p \)-rational for all \( p \)) and the imaginary quadratic fields for which we recall some history.

6.1. The \( p \)-rationality of imaginary quadratic fields. — After a work by Onabe [26] (with a correction to be made in the case \( p = 2 \)), the subject was studied by Angelakis and Stevenhagen [1, Thm. 4.4] in a different (but essentially equivalent) setting. Indeed, it is immediate to see that to have a minimal absolute abelian Galois group, isomorphic to \( \mathbb{Z}^2 \times \prod_{n \geq 1} \mathbb{Z}/n \mathbb{Z} \), is equivalent, for the imaginary quadratic field \( K \), to be \( p \)-rational for all \( p \), what we have explained and generalized for any number field in [11, §1.1].

6.1.1. Necessary and sufficient conditions. — Let \( K = \mathbb{Q}(\sqrt{-d}) \) be an imaginary quadratic field and let \( p \) be any prime number. Then \( K \) is \( p \)-rational if and only if \( W_K = 1 \) and the \( p \)-Hilbert class field \( H_K \) is contained in \( K \).

For \( p = 2 \), the conditions are given in Example 1.3 about complex and real abelian fields of degree a power of 2. For \( p = 3 \), \( W_K \simeq \mathbb{Z}/3 \mathbb{Z} \) for \(-d \equiv -3 \pmod{9}\) and \(-d \neq -3\). Then for \( p > 3 \), we get \( W_K = 1 \), but there is no immediate criterion for the inclusion \( H_K \subset K \) and we must use for instance the usual numerical computations of Section 3.2. We note that in [1, Table 1, §7] one has many examples of non-\( p \)-rational fields \( K \) whose \( p \)-class group is of order \( p \) (\( 2 \leq p \leq 97 \)), in complete agreement with our PARI Program I.

The Conjecture 7.1 of [1] may be translated into the similar one:

\textit{There are infinitely many imaginary quadratic fields, \( p \)-rational for all \( p \).}

Indeed, for \( K \) fixed, the class group is in general cyclic (from Cohen–Lenstra–Martinet heuristics) and for each \( p \)-class group the inclusion of the \( p \)-Hilbert class field in \( \tilde{K} \) depends on \( p \)-adic values of logarithms of ideals generating the \( p \)-classes (see Section 1 and Remark 6.1 below), whose probabilities are without mystery; but no direction of proof is known and the fact that the set of prime divisors of the class numbers increases as \( d \to \infty \) implies some rarefaction of such fields:

In \([b, B] = [1, 10^6]\) the proportion is 0.0766146 (46576 solutions for 607926 fields), in \([b, B] = [10^6, 10^8 + 10^5]\) it is 0.0697357, in \([10^9; 10^9 + 10^5]\) it is 0.0454172, and in \([10^{11}, 10^{11} + 10^5]\) it is 0.0379389 (2306 solutions for 60782 fields).

6.1.2. Program. — The following program gives very quickly, in any interval \([b, B]\), the set of imaginary quadratic fields which are \( p \)-rational for all \( p \geq 2 \); for this, it verifies the \( p \)-rationalities for \( p = 2, 3 \), and when \( p \) divides the class number:

\[
\begin{align*}
\text{b}=1; \text{B}=150; \text{Lrat}=\text{listcreate}; \text{m}=0; \text{for}( \text{d}= \text{b}, \text{B}, \text{if}( \text{core}( \text{d})!= \text{d}, \text{next}); \text{P}=\text{x}^2+\text{d}; \text{K}=\text{bnfinit}( \text{P}, 1); \\
\text{h}=\text{component}(\text{component}(\text{component}( \text{K}, 8), 1), 1); \text{hh}=\text{component}(\text{factor}(6* \text{h}), 1); \\
\text{t}=\text{component}(\text{matsize}( \text{hh}), 1); \text{for}( \text{k}=1, \text{t}, \text{p}=\text{component}( \text{hh}, \text{k}); \text{n}=2; \text{if}( \text{p}=2, \text{n}=3); \\
\text{Kpn}=\text{bnrinit}( \text{K}, \text{p}^\text{n}); \text{Hpn}=\text{component}(\text{component}( \text{Kpn}, 5), 2); \text{e}=\text{component}(\text{matsize}( \text{Hpn}), 2); \\
\end{align*}
\]
G. Gras

R=0;for(j=1,e,c=component(Hpn,e-j+1);if(Mod(c,p)==0,R=R+1));
T=0;if(R>2,T=1;break));if(T==0,m=m+1;listinsert(Lrat,-d,m)));print(Lrat)

[-1,-2,-3,-5,-6,-10,-11,-13,-19,-22,-26,-29,-37,-38,-43,-53,-58,-59,-61,
-67,-74,-83,-86,-101,-106,-118,-122,-131,-134,-139,-149\dots

[-1000058,-1000099,-1000117,-1000133,-1000138,-1000166,-1000211,-1000213,
-1000214,-1000253,-1000291,-1000333,-1000357,-1000358,-1000381,-1000394\dots

[-10000000019,-10000000058,-10000000061,-10000000069,-10000000118,
-10000000147,-10000000198,-10000000277,-10000000282,-10000000358]\dots

[-123456789062,-123456789094,-123456789133,-123456789194,-123456789322,
-123456789403,-123456789419,-123456789451,-123456789563,-123456789587]\dots

Remark 6.1. — Let $K$ be an imaginary quadratic field and $p > 3$; the Log function is nothing else than the usual logarithm. Then, using the property relying on the characterization $T_K = \text{Ker}(\text{Log})$, $K$ is not $p$-rational as soon as there exists an ideal $a$, whose class is of order $p^e \neq 1$, such that $\log(a) \in \log(U_K)$ which is equivalent to $\alpha = \xi \cdot w^p$, where $a^p = (\alpha)$ and $\xi \in \bigoplus_{p^f \mid p} \mu_{p^f - 1}$ where $f \in \{1, 2\}$ is the residue degree of $p$. For instance, in $K = \mathbb{Q}(\sqrt{-383})$, for $p = 17$, the $p$-class group is generated by the class of $1 \mid 2$ such that $1^{17} = (\alpha)$ where $\alpha = \frac{711 + \sqrt{-383}}{2}$ and $\log(\alpha) \equiv 0 \pmod{17^2}$; since we have $\log(U_K) = 17(\mathbb{Z}_{17} \oplus \mathbb{Z}_{17}\sqrt{-383})$, $K$ is not 17-rational. So it should be easy to elaborate PARI programs using this point of view.

6.2. Application to a conjecture of Hajir–Maire. — In [18, Conj. 0.2 and 4.16] is proposed the following conjecture as a sufficient condition to construct extensions of number fields whose Galois group is a suitable uniform pro-$p$-group with arbitrary large Iwasawa $\mu$-invariant:

**Given a prime $p$ and an integer $m \geq 1$, coprime to $p$, there exist a totally imaginary field $K_0$ and a degree $m$ cyclic extension $K/K_0$ such that $K$ is $p$-rational.**

6.2.1. Analysis of the conjecture. — Under Leopoldt’s conjecture, we have seen that $K_0$ must be itself $p$-rational, so the computations in Section 6.1 show that, in practice, we may fix $K_0$ to be any imaginary quadratic field, $p$-rational for all $p$, since they are very numerous. Then one has only to choose $p$ and $m$ and find a degree $m$ cyclic $p$-rational extension of $K_0$. Consider such a field $K_0 = \mathbb{Q}(\sqrt{-d})$; we know that $\text{Gal}(K^{ab}/K)$, its absolute abelian Galois group, is isomorphic to $\hat{\mathbb{Z}}^2 \times \prod_{n \geq 1} \mathbb{Z}/n\mathbb{Z}$, giving a countable basis of cyclic extensions of degree $m$, coprime to $p$, and the defect of the conjecture would say that any degree $m$ cyclic extension $K$ of $K_0$ is non-$p$-rational (this coming essentially from the $p$-class group and/or the normalized $p$-adic regulator of $K$, since one can easily realize $W_K = 1$ for infinitely many $K$). The Cohen–Lenstra–Martinet heuristics [4, 5] show that infinitely many cyclic extensions of degree $m$ may have trivial $p$-class group, so that we must focus on the case of $p$-adic properties of units of such fields.

For simplicity, we restrict ourselves to extensions $K/K_0$ unramified at $p$ since in the non-$p$-part of $K^{ab}/K$, the inertia groups at the $p$-places are finite and it remains infinitely many choices.
6.2.2. **Study of the relative extension** $K/K_0$. — Let $G = \text{Gal}(K/K_0) \simeq \mathbb{Z}/m\mathbb{Z}$; then $E_K/\mu_K$ (still denoted by abuse $E_K$) is a $G$-module of $\mathbb{Z}$-rank $m-1$ such that $N_{K/K_0}(E_K) = 1$, where the norm $N_{K/K_0}$ may also be understood as the “algebraic norm” in $\mathbb{Z}[G]$. It is well known, from generalized Herbrand’s theorem (e.g., [10, Lem. I.3.6]), that there exists a “Minkowski unit” $\eta \in E_K$ generating a $\mathbb{Z}[G]$-module $E_K'$ of prime to $p$ index in $E_K$; so $E_K'$ is a monogenic $\mathbb{Z}[G]/(N_{K/K_0})$-module.

Thus $\mathcal{R}_K$ is $p$-adically equivalent to a Frobenius determinant, product of components, indexed with the $p$-adic characters $\theta \neq 1$ of $G$, of the form $\text{Reg}_p^\theta(\eta) = \prod_{\varphi \mid \theta} \text{Reg}_p^\varphi(\eta)$ where $\varphi$ runs trough a set of $\mathbb{Q}_p$-conjugates of some irreducible characters of $G$.

The field of values of $\varphi$ only depend on the rational character $\chi$ such that $\varphi \mid \theta \mid \chi$ and is denoted $C_\chi$; thus the $\text{Reg}_p^\varphi(\eta)$ are $C_\chi$-linear combinations of terms of the form $\frac{1}{p} \log(\eta^\sigma)$, $\sigma \in G$, and the probabilities of $\text{Reg}_p^\varphi(\eta) \equiv 0 \pmod{p}$ depend on the residue degree $f$ of $p$ in $C_\chi$ and are conjecturally at most in $\frac{O(1)}{p^f}$ [12, §4.1]. Then each case ($p$ being fixed) strongly depends on the selected value of $m$, but the probability of non-$p$-rationality is a constant $\pi(p,m)$ whatever the choice of $K$.

This gives an incredible probability to have $\mathcal{R}_K \equiv 0 \pmod{p}$ for all these cyclic fields of degree $m$; moreover this concerns $K_0$ fixed among (conjecturally) infinitely many fields.

**Remark 6.2.** — The above reasoning is valid if we take $K$ as the compositum of $K_0$ with a real cyclic extension $K_1$ of degree $m \neq 0 \pmod{p}$ of $\mathbb{Q}$. If for instance $m$ is odd, $K$ is $p$-rational if and only if $K_1$ is $p$-rational and $\mathcal{O}_E^{(1)} = 1$ since $\mathcal{R}_K = \mathcal{R}_{K_1} = 1$. So in practice, varying $K_1$, we are certain to obtain, numerically, a solution. To prove that it is always possible is not yet accessible since we do not have any example, for each $m$, of a field $K_1$, $p$-rational for all $p$ (which is not sufficient to get the $p$-rationality of $K$). We shall illustrate the two contexts ($K/\mathbb{Q}$ non-abelian and $K = K_0K_1$).

6.2.3. **Numerical examples.** —

(i) Take $K_0 = \mathbb{Q}(\sqrt{-3})$ and $m = 6$ to define $K$ by means of Kummer theory. Put

$$K = K_0(\sqrt[6]{u + v \sqrt{-3}}), \quad u,v \in \mathbb{Z};$$

then $K$ is defined by the polynomial $P = x^{12} - 2ux^6 + u^2 + 3v^2$ and $r := r_2+1 = 7$. The program verifies that $P$ is irreducible since $u,v$ are random. The $p$-rationality is tested for $5 \leq p \leq 100$ and in most cases the $p$-rationality holds giving many possibilities to illustrate the conjecture.

We give the list of exceptions obtained in an execution of the program (among about one hundred $u + v \sqrt{-3}$):

```
{n=2;r=7;b=5;B=100;for(N=1,100,u=random(10^3);v=random(10^3);P=x^12-2u*x^6+u^2+3*v^2;if(polisirreducible(P)!=1,next);K=bnfinit(P,1);forprime(p=b,B,Kpn=bnrinit(K,p^n);Hpn=component(component(Kpn,5),2);e=component(matsize(Hpn),2);R=0;for(k=1,e,c=component(Hpn,c+1);if(Mod(c,p)==0,R=R+1));if(R>r,print(u," ",v," K is not ",p,"-rational")));}}
```

<table>
<thead>
<tr>
<th>u</th>
<th>v</th>
<th>K is not 7-rational</th>
<th>u</th>
<th>v</th>
<th>K is not 37-rational</th>
</tr>
</thead>
<tbody>
<tr>
<td>705</td>
<td>960</td>
<td></td>
<td>705</td>
<td>960</td>
<td></td>
</tr>
</tbody>
</table>
(ii) For the compositum $K$ of $K_0 = \mathbb{Q}(\sqrt{-1})$ with the cyclic extension of $\mathbb{Q}$ of degree 5 and conductor 11, we obtain that $K$ is not $p$-rational for $p = 761$, up to $10^4$. To have $C_{\ell} K \neq 1$, it is necessary that $N_{K/K_0}(C_{\ell} K) = N_{K_0/K_1}(C_{\ell} K) = 1$, which explains the rarity of the non-$p$-rationalities:

\[ \text{Publications mathématiques de Besançon – 2019/2} \]
We note that Theorem 2.1 and Corollary 2.2 are still valid for a test of any incomplete p-rationality, using [10, Thm. I.4.5 & Cor. I.4.5.4] for a more general support $P$: the value of $n_0$ is the same assuming $c_p = 1$ for all $p \in P$ (otherwise the suitable modulus is $\prod_{p \in P} p^{e_p n_0}$).

The case $P = \emptyset$ leads to the $p$-class group $\mathcal{O}_K$ of $K$. So, when $P$ varies from $\emptyset$ to the set $\{p \mid p\}$ of $p$-places, the corresponding heuristics vary from the classic ones to less known ones. The question concerning $K$ fixed and $p \to \infty$ is vital since the case $\#T_K^0 = 1$ for all $p \gg 0$ is obvious contrary to the case of $\#T_K^{[p]}$ for all $p \gg 0$.

6.3.2. $\{p\}$-rationality for imaginary quadratic fields. — For an imaginary quadratic fields with $p$ split into $p'$ and $P = \{p\}$ one gets:

$$\#T_K^{[p]} = \#(\mu_{K_p}/\mu_K) \cdot [H_K : H_K \cap \overline{K}^{(p)}],$$

where $\overline{K}^{(p)}$ is a $\mathbb{Z}_p$-extension.

The following program gives the non-$\{p\}$-rationality for quadratic fields $\mathbb{Q}(\sqrt{-d})$, $d \in [b, B]$ and $p \in [bp, Bp]$:

```plaintext
{b=1;B=10^3;bp=2;Bp=10^4;for(dd=b,B,if(core(dd)!=dd,next);d=-dd;
P=x^2-d;K=bnfnit(P,1);forprime(p=bp,Bp,if(kronecker(d,p)!=1,next);
{n=2;if(p==2,n=3);p1=component(component(idealfactor(K,p),1),1);
P=x^2-d;K=bnfnit(P,1);forprime(p=bp,Bp,if(kronecker(d,p)!=1,next);
{b=1;B=10^3;bp=2;Bp=10^4;for(dd=b,B,if(core(dd)!=dd,next);d=-dd;
P=x^2-d;K=bnfnit(P,1);forprime(p=bp,Bp,if(kronecker(d,p)!=1,next);
{n=2;if(p==2,n=3);p1=component(component(idealfactor(K,p),1),1));}
p=component(matsize(Hpn),2);R=0;for(k=1,e,c=component(component(idealfactor(K,p),1),1));
bp=2;Bp=10^4;for(dd=b,B,if(core(dd)!=dd,next);d=-dd;
P=x^2-d;K=bnfnit(P,1);forprime(p=bp,Bp,if(kronecker(d,p)!=1,next);
{n=2;if(p==2,n=3);p1=component(component(idealfactor(K,p),1),1));}
p=component(matsize(Hpn),2);R=0;for(k=1,e,c=component(component(idealfactor(K,p),1),1));
if(Mod(c,p)==0,R=R+1);if(R>1,print("d","d","rk(T)="));
}
)
}
```

We get the following non-$\{p\}$-rational fields (in the above intervals):

- $d \in \{-33, -57, -65, -105, -119, -129, -145, -161, -177, -185, \ldots, -935, -943, -959, -969, -985, -993\}$, for $p \mid 2$,
- $d \in \{-107, -302, -362, -419, -503, -509, -533, -602, -617, -713, -863, -974\}$, for $p \mid 3$,
- $d \in \{-166, -439, -449, -479, -601, -611, -739, -761, -874\}$, for $p \mid 5$,
- $d \in \{-374, -530, -794, -831, -859, -894\}$, for $p \mid 7$,
- $d = -758$, for $p \mid 11$,
- $d \in \{-458, -998\}$, for $p \mid 13$,
- $d = -383$, for $p \mid 17$.

Remarks 6.4. — (i) In an imaginary quadratic field in which $p \neq 2$ splits, the $p$-rationality is equivalent to the $\{p\}$-rationality: indeed, one verifies that

$$\overline{K}^{(p)} \overline{K}^{(p')} = \overline{K},$$

and that $\overline{K}^{(p)} \cap \overline{K}^{(p')} = \overline{K} \cap H_K$

($\overline{K} \cap H_K$ is contained in the “anti-cyclotomic” $\mathbb{Z}_p$-extension of $K$); thus the $p$-rationality implies the $\{p\}$ and $\{p'\}$-rationalities, the converse being obvious.

For instance, for $p = 3$, $K = \mathbb{Q}(\sqrt{-491})$ where $\mathcal{O}_K \simeq \mathbb{Z}/9\mathbb{Z}$, we have $H_K = \overline{K}^{(p)} \cap \overline{K}^{(p')}$ (whence 3-rationality); the class of $q | 11$ is of order 9 and $q^9 = (\frac{1}{2}(95595 + 773\sqrt{-491}))$ with $\log(\frac{1}{2}(95595 + 773\sqrt{-491})) \equiv 3\sqrt{-491} \pmod{27}$ giving again all the rationalities as expected.

So we may use the above program computing the ray class group modulo $p^{n_0}$ which is much faster than the program for the ray class group modulo $p^{n_0}$.

(ii) In the case $p = 2$ split in $K$, besides the use of Program I (Section 3.2), the computations may be handled with the use of the 2-adic logarithm as in [10, Ex. III.5.2.2] for $K = \mathbb{Q}(\sqrt{-15})$, showing its $\{p\}$-rationality despite the fact that $K$ is not 2-rational.
For instance, the invariant about Frobenius determinants (see [12, Heuristique Principale, §4.2.2] about the more general problem). In terms of p-adic representation theory and the nature of the p-adic characters of Gal(K/Q), via factorization of Frobenius determinants (see [12, Heuristique Principale, §4.2.2] about the more general question of an algebraic number).

We have given generalization of Leopoldt conjecture in this incomplete framework and conjectured a formula for the Zp-rank of $U_K^\Sigma \cap \overline{E}_K$ which is the set of $\bar{e} \in \overline{E}_K$ in $U_K$ whose component on $U_K^P$ is trivial (see [10, Strong p-adic conjecture, III(f), Rem. 4.11.2, 4.11.4, 4.12.1 & 4.12.3] for detailed statements; a 2013 arXiv publication by Dawn C. Nelson [25] discovers again the same kind of results). We have published, as complement, the text: “Practice of the incomplete p-ramification over a number field – History of abelian p-ramification” [15].

7. Conclusion

As we have seen, Galois number fields $K$ containing units of infinite order are in general p-rational for “almost all $p \gg 0$” despite the fact that we have no information on $\mathcal{R}_K$ modulo $p$ for $p \to \infty$. More precisely, probabilities are given (in an heuristic approach) by means of p-adic representation theory and the nature of p-adic characters of Gal(K/Q), via factorization of Frobenius determinants (see [12, Heuristique Principale, §4.2.2] about the more general question of an algebraic number).

The case of small primes $p$ is different because of local $p$th roots of unity and $p$-class groups. For instance, the invariant $\mathcal{W}_K = (\bigoplus_{p \mid p} \mu_{K_p})/\mu_K$, depending on the splitting of $p$ in $K(\mu_p)/\mathbb{Q}$, may be non-trivial (e.g., the most common case $p = 2$).

For a Galois number field, with sufficiently ramified primes and $p \mid [K : \mathbb{Q}]$, the rank of the $p$-class group may be an obstruction to the $p$-rationality because of “genera theory” in $K/Q$; the case where $[K : \mathbb{Q}] \neq 0 \pmod{p}$ leads also to an obstruction as soon as

$$\text{rk}_p(\mathcal{O}_K) > r = r_2 + 1,$$

and this fact is rather strange in a probabilistic point of view. If $K$ is real and if $[K : \mathbb{Q}] \neq 0 \pmod{p}$ then $\mathcal{O}_K^{\infty} = \mathcal{O}_K$ since $K$ is the cyclotomic $\mathbb{Z}_p$-extension, totally ramified at $p$.

However, for $K$ fixed and $p \gg 0$, one gets $\mathcal{O}_K^{\infty} = \mathcal{W}_K = 1$ and the most deep and mysterious invariant about $p$-rationality is the normalized p-adic regulator which then becomes, for $K$ real and $p$ unramified,

$$\mathcal{R}_K = \frac{1}{p^{r_1+r_2-1}} R_K$$

($R_K$ being the usual $p$-adic regulator [31, §5.5]).

In terms of $p$-rationality, the real case may be written in a conjectural way as follows (for more information and generalizations to Jaulent’s conjecture replacing $E_K$ by the $G$-module generated by an algebraic number $\eta$, see [12, Thm 1.1 & Heuristic 7.4]):

**Conjecture 7.1.** — Let $K/Q$ be a real Galois extension of Galois group $G$ and let $\eta \in E_K$ be a Minkowski unit (i.e., a unit generating a sub-$G$-module of finite index of $E_K$). The
probability of $R_K \equiv 0 \pmod{p}$ is at most:

$$\frac{1}{p^\log_2(p) / \log(c_0(\eta)) - O(1)}, \text{ for } p \to \infty,$$

where $c_0(\eta) = \max_{\sigma \in G}(|\eta^\sigma|)$, and $\log_2 = \log \circ \log$. Under the principle of Borel–Cantelli, the number of primes $p$ such that $K$ is non-$p$-rational is finite.

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References


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