A Note on the Class Number of Imaginary Quadratic Fields*

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1. Introduction. The object of this note is to make some observations on imaginary quadratic fields with a given class number. We give a different proof of a modified form of the theorem of Heilbronn and Linfoot [1] to the effect that there are at most 10 imaginary quadratic fields with class number 1. The nine known fields have discriminants $-3, -4, -7, -8, -11, -19, -43, -67, -163$. The existence or nonexistence of a 10th field remains an unsolved problem. We hasten to add that the arguments given below shed no new light on this famous problem.

Let $h(d)$ be the class number of the imaginary quadratic field $\mathbb{Q}(\sqrt{-D})$ with $D > 0$ and square free and with discriminant $-d = -D$ or $-4D$.

Heilbronn [2] proved the famous conjecture of Gauss that $h(d) \to \infty$ as $d \to \infty$, and C. L. Siegel [3] proved the stronger result that for every $\epsilon > 0$, there exists a constant $d(\epsilon)$ such that for $d > d(\epsilon)$,

$$h(d) > d^{1/2-\epsilon}.$$ 

Both these results imply of course that the number of fields with a given class number must be finite; in particular there exists $d_0$ such that for $d > d_0$, $h(d) > 1$. Unfortunately, the constant $d_0$ cannot be effectively determined from either proof.

The proof of the theorem of Heilbronn and Linfoot was effected by modifying Heilbronn's proof of Gauss's conjecture, keeping control of the error, and it might be expected that Siegel's proof can be similarly modified, as indeed it can. We therefore prove the following:

**Theorem A.** There exists an effectively calculable constant $p_0$ such that if $p_1 \geq p_2 \geq p_0$ and

$$h(p_1) = h(p_2) = 1,$$

then $p_1 = p_2$.

It should perhaps be noted that if $h(d) = 1$, then $d$ is a prime.

We shall defer for the time being an explicit evaluation of $p_0$. As we shall see in the course of the proof, we have a parameter at our disposal which may be expected to aid in determining the most economical value of $p_0$.

By modifying our proof somewhat, we can prove the slightly more general

**Theorem B.** For any integer $h_0 \geq 1$, there exists an effectively calculable constant $p_0(h_0)$ such that if $d_1 \geq d_2 \geq p_0(h_0)$

and

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CLASS NUMBER OF IMAGINARY QUADRATICS FIELDS

\[ h(d_1) = h(d_2) = h_0, \]

then

\[ d_1 = d_2. \]

We restrict our attention to a proof of Theorem A.

2. Proof of Theorem A. The proof is as noted above an adaptation of Siegel's argument. We shall state the results needed.

Let \( K \) be an algebraic extension of the rationals of degree \( n \) with \( \gamma_1 \) real and \( 2\gamma_2 \) complex conjugates where \( \gamma_1 + 2\gamma_2 = n \). Put \( q = \gamma_1 + \gamma_2 \), and let \( x_1, x_2, \ldots, x_n \) be \( n \) positive real variables subject to the restriction that \( x_{\gamma_1+i} = x_l \) \((l = \gamma_1 + 1, \ldots, \gamma_1 + \gamma_2)\).

Let

\[ N(x) = \prod_{i=1}^{n} x_i \quad \text{and} \quad S(x) = \sum_{i=1}^{n} x_i \]

and let

\[ \zeta_K(s) = \sum_{\mathfrak{a}} \frac{1}{N(\mathfrak{a})^s} \]

be the Dedekind zeta function for the field \( K \), where \( \mathfrak{a} \) runs over the ideals of \( K \) and \( N(\mathfrak{a}) \) denotes the norm of the ideal \( \mathfrak{a} \). Hecke (see e.g. Landau [4]) derived the functional equation for \( \zeta_K(s) \) via the formula

\[ \phi(s) = \pi^{-n/2}2^{-\gamma_1}d^{1/2} \Gamma \left( \frac{s}{2} \right) \Gamma(1-s) \zeta_K(s) \]

\[ = \frac{\lambda_K}{s(s-1)} + \sum_{\mathfrak{a}} \left[ \cdots \int (N(x)^{s/2} + N(x)^{(1-s)/2}) \right] \]

\[ \times \exp \left[ -\pi N(\mathfrak{a})^{2/n} |d|^{-1/n} S(x) \right] \frac{dx_1 \cdots dx_q}{x_1 \cdots x_q} \]

where

\[ (2) \quad \lambda_K = (2\pi)^{-\gamma_1} |d|^{1/2} \alpha, \]

\( d \) is the discriminant of \( K \) and \( \alpha \) is the residue of \( \zeta_K(s) \) at its simple pole at \( s = 1 \).

The first inference to be drawn from (1) is that for \( 0 < s < 1 \),

\[ \phi_K(s) > \frac{\lambda_K}{s(s-1)} + |d|^{1/2} \exp \left[ -2\pi n \right] 2^{-n}. \]

The proof is straightforward; the integrand being positive, we neglect all but the term \( \mathfrak{a} = (1) \) in the sum and integrate only over \( |d|^{1/n} \leq x_i \leq 2|d|^{1/n} \) \((i = 1, 2, \ldots, q)\). Though the constant \( \exp \left[ -2\pi n \right] 2^{-n} \) may be improved considerably, the order of magnitude as a function of \( |d| \) may not. It should perhaps be remarked that it would be interesting to find a proof of (3) which does not use (1).

Now let \( d \) be the discriminant of a quadratic field and let
be the Kronecker symbol; let

\[
\chi_d(n) = (d/n)
\]

be the L-function belonging to the primitive character \(\chi_d\).

If \(K\) is a quadratic field with discriminant \(-d\) \((d > 0)\) with class number \(h(d)\), then

\[
\zeta_K(s) = \zeta(s)L(s, \chi_d)
\]

and moreover in this case

\[
L(1, \chi_d) = \left(\pi/\sqrt{d}\right) h(d).
\]

These are well-known results (see e.g. Ayoub [6, Chapter V]). Assume now that \(K_1\) and \(K_2\) are imaginary quadratic fields with class number 1 and suppose that their discriminants are \(-p_1\) and \(-p_2\), where, as remarked above, \(p_1\) and \(p_2\) are primes. Suppose that \(K_3\) is the quadratic field generated by \((p_1p_2)^{1/2}\) and suppose also that \(K\) is the biquadratic field generated by \((-p_1)^{1/2}\) and \((-p_2)^{1/2}\), that is \(K_1\) and \(K_2\). Then since \(p_i = 3\) \((\text{mod 4})\) for \(p_i > 8\), it is a simple calculation to show that the discriminant of \(K_3\) is \(p_1p_2\), the discriminant of \(K\) is \((p_1p_2)^2\) and moreover for \(K\) we have \(\gamma_2 = 2\) and of course \(\gamma_1 = 0\). An examination of the decomposition of rational primes \(p\) in the field \(K\) yields the result (see Siegel [3])

\[
\zeta_K(s) = \zeta(s)L(s, \chi_{-p_1})L(s, \chi_{-p_2})L(s, \chi_{p_1p_2}).
\]

Since \(K_1\) is assumed to have class number 1, it follows from (2), (5) and (6) that \(\lambda_{K_i} = 1/2\). If then \(\varphi_{K_i}(s) \leq 0\), then from (3) we should get

\[
1 > s(1 - s)p_i^{s/2} \exp \left[-4\pi|^22^{-1}\right].
\]

Consequently if \(s_0 \in (3/4, 1)\), we can find \(p_0'(s_0)\) for which (8) is false. Therefore, for \(p_1 \geq p_0'(s_0)\) we have \(\varphi_{K_1}(s_0) > 0\). In other words,

\[
L(s_0, \chi_{-p_1})\zeta(s_0) > 0.
\]

But since \(\zeta(s) < 0\) for \(0 < s < 1\), it follows that

\[
L(s_0, \chi_{-p_1}) < 0.
\]

Since \(L(1, \chi_{-p_1}) > 0\) from (5), (and \(L(s, \chi)\) is continuous) we infer that there exists \(s_1\), with \(s_0 < s_1 < 1\), such that

\[
L(s_1, \chi_{-p_1}) = 0.
\]

We now apply (3) together with (7), using (9), to get

\[
0 > \frac{\lambda_K}{s_1(s_1 - 1)} + c_1(p_1p_2)^{s_1},
\]

where by (7), we have

\[
\lambda_K = (2\pi)^{-2}2p_1p_2L(1, \chi_{-p_1})L(1, \chi_{-p_2})L(1, \chi_{p_1p_2}).
\]
On the other hand, if $\chi$ is a real character mod $k$, then we have the inequality
\begin{equation}
L(1, \chi) < 3 \log k = c_2 \log k
\end{equation}
which is readily derived by partial summation.

We use (6) for $L(1, \chi_{p_{1}^{-}})$ and $L(1, \chi_{p_{1}^{+}})$ and (12) for $L(1, \chi_{p_{1}p_{2}^{-}})$ in (10) and (11)
and infer that
\begin{equation}
0 > \frac{c_{3}(p_{1}p_{2})^{1/2} \log p_{1}p_{2}}{s_{1}(s_{1} - 1)} + c_{4}(p_{1}p_{2})^{s_{1}}
\end{equation}
or
\begin{equation}
\log p_{1}p_{2} > c_{5}s_{1}(1 - s_{1})(p_{1}p_{2})^{s_{1} - 1/2}.
\end{equation}
It is elementary to show that there exists a constant $c_{6}$ such that
\begin{equation}
1 - s_{1} > c_{6}/(p_{1})^{1/2} \log p_{1}
\end{equation}
but we shall use the much deeper result of Rosser [5], viz.
\begin{equation}
1 - s_{1} > \pi/6 (p_{1})^{1/2}
\end{equation}
even though (14) could be used for numerical purposes. Putting (15) in (13), we get for $p_{1} > p_{0}(s_{0})$
\begin{equation}
\log p_{1}p_{2} > c_{7}(p_{1}p_{2})^{s_{1} - 1/2}p_{1}^{1/2}.
\end{equation}
The entire argument, however, is symmetric in $p_{1}$ and $p_{2}$, and we therefore infer
that for $p_{2} > p_{0}''(s_{0})$
\begin{equation}
\log p_{1}p_{2} > c_{8}(p_{1}p_{2})^{s_{1} - 1/2}p_{2}^{1/2}.
\end{equation}
From (16) and (17) it now follows that if $p_{1}, p_{2} > p_{0}'''(s_{0}) = \max (p_{0}', p_{0}'')$, then
\begin{equation}
\log^{2} p_{1}p_{2} > c_{9}(p_{1}p_{2})^{2s_{1} - 3/2}.
\end{equation}
Since we assumed that $s_{0} > 3/4$, (18) leads to a contradiction if $p_{1}, p_{2} > p_{0}^{(iv)}(s_{0})$.
Thus, finally, if $p_{0}(s_{0}) = \max (p_{0}'', p_{0}^{(iv)})$, we get a contradiction—hence $p_{1} = p_{2}$.

It should be noted finally that all of the constants $c_{1}, c_{2}, \ldots, c_{9}$ as well as the $p_{0}$'s are effectively calculable.

Moreover it should be observed that in numerical calculations, we have in addition
the parameter $s_{0}$ at our disposal.

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