CYCLOTOMIC INVARIANTS FOR PRIMES BETWEEN 125000 AND 150000

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Abstract. Computations by Iwasawa and Sims, by Johnson, and by Wagstaff have determined certain important cyclotomic invariants for all primes up to 125000. We extended their results to 150000, basing our work on a recently computed list of irregular primes and using a new method.

1. Introduction

Since 1978, when Wagstaff [10] published the results of his extensive computations, one knows the values of certain important cyclotomic invariants, notably the Iwasawa invariants $\lambda_p$ and $\mu_p$, for all primes $p < 125000$. The first, and hardest, step in these computations is the determination of irregular primes. Recently Tanner and Wagstaff [9], returning to this theme, extended the list of irregular primes to 150000 and obtained partial results about the cyclotomic invariants.

The present note is a report on our computations completing the determination of these invariants up to $p < 150000$. Since at the primes of this size the earlier methods of computation no longer are efficient, it was necessary to develop new techniques. A description of our method, based on a suitable combination of congruences for Bernoulli numbers, is included.

2. The results

Let $p$ be an odd prime. For $n \geq 0$, let $K_n$ denote the cyclotomic field of $p^{n+1}$th roots of 1, and let $h_n$ and $A_n$ be the class number and $p$-class group, respectively, of $K_n$. As usual, write

$$h_n = h_n^+ h_n^-, \quad A_n = A_n^+ \oplus A_n^-,$$

where $h_n^+$ and $A_n^+$ are the class number and $p$-class group, respectively, of the field $K_n \cap \mathbb{R}$.

It is well known that the triviality of $A_n$, for all $n \geq 0$, is equivalent to the triviality of $A_0$. If these groups are nontrivial, $p$ is called irregular. This is the

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case if and only if \( p \) divides \( B_2 B_4 \cdots B_{p-3} \), where \( B_t \) are Bernoulli numbers (in the even suffix notation).

If \( p \) divides \( B_t \) with \( t \in \{2, 4, \ldots, p-3\} \), then \( (p, t) \) is called an irregular pair. We let \( r_p \) denote the number of such pairs, the index of irregularity of \( p \).

Expressed in a brief form, the results of our computations read as follows:

for every \( p \) between 125000 and 150000,

\[
\begin{align*}
&\text{(1)} \quad A_n^- \simeq (\mathbb{Z}/p^{n+1}\mathbb{Z})^r_p \quad (n = 0, 1, \ldots), \\
&\text{(2)} \quad \text{ord}_p(h_0^-) = \text{ord}_p(B_2 B_4 \cdots B_{p-3}),
\end{align*}
\]

where \( \text{ord}_p(a) \) stands for the exponent of \( p \) in the canonical decomposition of \( a \).

Actually, we know that \( A_n^+ \) is trivial for these \( p \), so that (1) and (2) remain true if \( A_n^- \) and \( h_0^- \) are replaced by \( A_n \) and \( h_0 \), respectively. The triviality of \( A_n^+ \) was proved by Tanner and Wagstaff [9] in conjunction with the verification of Fermat’s Last Theorem for prime exponents \( p < 150000 \); see, e.g., Corollary 8.19 in Washington’s book [11].

The formulas (1) and (2), together with the result \( A_n^+ = 1 \), had been verified by Wagstaff [10] for \( p < 125000 \), and earlier by Johnson [2], [3], [4] in shorter ranges. Computations for verifying (1) were initiated by Iwasawa and Sims [1].

By Iwasawa’s general result,

\[
\text{ord}_p(h_n^+) = \lambda_p n + \nu_p, \quad \text{ord}_p(h_n^-) = \lambda_p^- n + \nu_p^-
\]

for all \( n \) large enough, say \( n \geq n_p \), where \( \lambda_p, \lambda_p^-, \nu_p, \nu_p^- \) are integers (\( \lambda_p, \lambda_p^- \) nonnegative) independent of \( n \). Notice that the \( \mu \)-invariant vanishes by the theorem of Ferrero and Washington. Given that the groups \( A_n^+ \) are trivial, (1) is equivalent to

\[
\lambda_p = \lambda_p^- = \nu_p = \nu_p^- = r_p, \quad \text{minimal } n_p = 0
\]

(for this and the following facts, we refer to [11], especially §10.3).

We may decompose \( \lambda_p^- = \lambda^{(2)} + \lambda^{(4)} + \cdots + \lambda^{(p-3)} \), where each \( \lambda^{(t)} \) is the \( \lambda \)-invariant associated with the \( p \)-adic \( L \)-function \( L_p(s, \omega^t) \), \( \omega \) being the Teichmüller character mod \( p \). Since \( \lambda^{(t)} \) is positive if and only if \( (p, t) \) is an irregular pair, the equation \( \lambda_p^- = r_p \) is equivalent to

\[
\lambda^{(t)} = 1 \quad \text{for each irregular pair } (p, t).
\]

To establish the results (1) and (2), it is enough to verify—and this is what we did—that none of the following three congruences hold for any irregular pair \( (p, t) \):

\[
\begin{align*}
&\text{(i)} \quad \frac{B_t}{t} \equiv \frac{B_{t+p-1}}{t+p-1} \pmod{p^2}, \\
&\text{(ii)} \quad B_t(\omega^{t-1}) \equiv 0 \pmod{p^2},
\end{align*}
\]
(iii) \( B_t \equiv 0 \pmod{p^2} \).

Here, \( B_t(\omega^{t-1}) = (1/p) \sum_{a=1}^{p-1} \omega^{t-1}(a)a \) is the first generalized Bernoulli number attached to \( \omega^{t-1} \), in fact, \( B_t(\omega^{t-1}) = -L_p(0, \omega^t) \). We point out that (ii) can be converted into a simple congruence mod \( p^2 \) between \( B_t \) and \( B_{t+p-1} \); see Propositions 6 and 2 in §4.

More precisely, the failures of (i) and (ii), for all \( t \) such that the pair \((p, t)\) is irregular, imply that \( \lambda_p = r_p \) and \( \nu_p = r_p \), respectively [11, p. 201], and the failure of (iii) then yields the equation (2). Observe that the congruences in (i)-(iii) hold modulo \( p \).

By Washington's heuristic arguments [6, p. 20] one expects that (1) and (2) remain true for all primes up to a very high limit. They should not be generally true, however.

3. The computations

If \( p \) is not too big, one can disprove (i)-(iii) by a fairly straightforward method involving basically the calculation of \( B_t \) and \( B_{t+p-1} \) mod \( p^2 \). In fact, such a method was employed by Johnson and Wagstaff for \( p < 125000 \). There is also another method presented in [1]; it is more sophisticated but still relies quite heavily on computations mod \( p^2 \).

For \( p \) close to 150000 we have to find a method which keeps computations mod \( p^2 \) to a minimum. We point out that in order that \( c^2 \) fit in a computer word, \( c \) should be below \( 2^{16} \), which for \( c \) around \( p/2 \) leads to the bound \( p < 1.3 \cdot 10^5 \).

Write \( p = 2m + 1 \). For an integer \( a \) prime to \( p \), let \( q_a \) denote the Fermat quotient of \( a \), i.e.,

\[
q_a \equiv \frac{a^{p-1} - 1}{p}, \quad 0 \leq q_a < p.
\]

Putting

\[
S_1 = \sum_{a=1}^{m} a^{t-1} q_a, \quad S_2 = \sum_{a=1}^{m} a^t q_a^2,
\]

\[
S_3 = \sum_{a=1}^{m} a^{t-1}, \quad S_4 = \sum_{0 < a < p/3} a^{t-1}, \quad S_5 = \sum_{p/3 < a < p/2} a^{t-2},
\]

we formulate the following criteria, where \((p, t)\) is assumed to be an irregular pair. The proofs will be presented in §4.

**Criterion 1.** If \( S_1 \not\equiv 0 \pmod{p} \), then (i) does not hold. If \( S_1 \equiv 0 \pmod{p} \), then either \( 2^t \equiv 1 \pmod{p} \) or (i) holds.

**Criterion 2.** If \( S_2 \not\equiv 0 \pmod{p} \), then (i) does not hold. If \( S_2 \equiv 0 \pmod{p} \), then either \( 2^{t-1} \equiv 1 \pmod{p} \) or (i) holds.
Criterion 3. If $2^l \not\equiv 1 \pmod{p}$, then (ii) is equivalent to
\[ S_3 \equiv (1-t)pS_1 \pmod{p^2} \]
and (iii) is equivalent to
\[ S_3 \equiv 0 \pmod{p^2}. \]

Criterion 4. If $2^{l-1} \not\equiv 1$ and $3^l \not\equiv 1 \pmod{p}$, then (ii) is equivalent to
\[ 3S_4 - (1-t)pS_5 \equiv -\left(\frac{2}{3}\right)^{t-2} \frac{3^l - 1}{2^{l-1} - 1} (1-t)pS_2 \pmod{p^2}. \]
If $3^l \not\equiv 1 \pmod{p}$, then (iii) is equivalent to
\[ 3S_4 - (1-t)pS_5 \equiv 0 \pmod{p^2}. \]

Criteria 1 and 2 always suffice to decide about the validity of (i), because the congruences $2^l \equiv 1$ and $2^{l-1} \equiv 1 \pmod{p}$ never hold simultaneously. Similarly, Criteria 3 and 4 are sufficient for (ii) and (iii) except when $2^l \equiv 3^l \equiv 1 \pmod{p}$. For the case of the last instance one can derive analogous criteria that work under the assumption $b^l \not\equiv 1 \pmod{p}$ for some other $b$ prime to $p$ (see §4).

There are 1079 irregular pairs with $125000 < p < 150000$. It turned out that all these pairs satisfy $2^l \equiv 1$ and $3^l \equiv 1 \pmod{p}$, so that one can disprove (i)-(iii) merely by using Criteria 2 and 4. The incongruence $2^l \not\equiv 1 \pmod{p}$ holds everywhere except at the pair $(130811, 52324)$. Thus, excluding this single pair, Criteria 1 and 3 apply to check the results.

In reality, we started with Criterion 1 without knowing of the above exception, and then went on with 2, 4, and 3 in this order.

We now describe the calculation of the sums $S_1, \ldots, S_5$.

To obtain $S_1$ and $S_2 \pmod{p}$ (as they are needed), one has to find $q_a$ which actually involves a computation mod $p^2$. We calculated the values of $q_a$ ($1 \leq a \leq m$) in cycles, passing from $q_a$ to $q_{2a}$ or, if $2a > m$, to $q_{p-2a}$. These are related to $q_a$ by a simple congruence mod $p$. Hence, only the first $q_a$ in each cycle actually requires computation mod $p^2$. In many cases (e.g., if 2 is a primitive root mod $p$ or if $m$ is a prime) there is but one cycle, and in our range, less than every hundredth irregular prime had more than 10 cycles. A similar method was employed by Johnson [2, pp. 391, 396] in another connection.

Rather than to $q_a$ only, we in fact applied this cycle method to the entire terms of $S_1$ and $S_2$. The same cycles were then used in the calculation of the remaining sums. When calculating $S_3$ and $S_4$ this way, one has to perform some computation mod $p^2$ inside the cycles, too, but the method still appears to be quite efficient. The computation of $S_5$ did not provide any serious problem, because this sum was needed mod $p$ only.
The first program run by us computed, except for $S_1$, two additional sums mod $p$, namely $S_2$ and

$$S_6 = \sum_{a=1}^{m} a' q_a.$$ 

This was a check both for the correctness of our summing method and for the irregularity of the given pairs $(p, t)$. Indeed, for an irregular pair, the latter sums vanish mod $p$ (see Proposition 3 below). There were also some further checks to assure that the Fermat quotients were correctly calculated. The running time for a single irregular pair was generally 12 to 15 sec.

The programs computing $S_3$ and $S_4$ mod $p^2$ took somewhat more time to execute: one irregular pair was settled in 25 to 45 sec. One simple check was provided by the congruences $S_3 \equiv S_4 \equiv 0 \pmod p$.

All programs were written in the language C and run on a VAX 6340 computer. After learning that the use of inline optimization (in the C-compiler version 3.0) may produce erroneous code, we ran all the programs once more without this option.

4. Proof of the criteria

The four criteria of the previous section will be proved by transforming the Bernoulli number congruences (i)–(iii) into congruences between the sums involved. The procedure is based on the following two congruences.

**Proposition 1.** Let $t$ be a positive even integer prime to $p$ and incongruent to 0 and 2 (mod $p-1$). Then

(a) $$\frac{B_t}{t} \equiv -\sum_{a=1}^{p-1} a^{t-1} v_a - \frac{t-1}{2} p \sum_{a=1}^{p-1} a^{t-2} v_a^2 \pmod{p^2},$$

where $v_a$ is the $p$-adic integer defined by $\omega(a) = a + v_p p$; furthermore,

(b) $$(b' - 1) \frac{B_t}{t} \equiv \sum_{a=1}^{p-1} (ba)^{t-1} \left[ \frac{ba}{p} \right] - \frac{t-1}{2} p \sum_{a=1}^{p-1} (ba)^{t-2} \left[ \frac{ba}{p} \right]^2 \pmod{p^2},$$

where $b$ is any rational integer with $2 \leq b \leq p - 1$ and $\lfloor x \rfloor$ denotes the largest integer $\leq x$.

**Proof.** The latter congruence, a sharpening of the Voronoi congruence, is due to Johnson [5, p. 261]; for a different proof see [8, p. 117].

The former congruence can be verified by an argument similar to one in [5, p. 253]: substitute $\omega(a) = a + v_p p$ in the equation $\sum_{a=1}^{p-1} \omega(a)^t = 0$, expand the $t$th power, and reduce mod $p^3$, noting that $\sum_{a=1}^{p-1} a^t \equiv pB_t \pmod{p^3}$. This last congruence is proved, e.g., in [5, p. 261].

From now on we assume that

$$t \in \{2, 4, \ldots, p-3\}.$$ 

Thus, in particular, $p > 3$. 

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Proposition 2. Excluding the case $t = 2$, we have
\[
\frac{B_{t+p-1}}{t + p - 1} - \frac{B_t}{t} \equiv -\frac{1}{2} p \sum_{a=1}^{p-1} a^{t} q_a^2 \pmod{p^2}.
\]

Proof. This follows from Proposition 1(a). Observe that $a^{p-1} - 1 \equiv pq_a \pmod{p^2}$, $v_a \equiv q_a \pmod{p}$. □

The next result is an easy consequence of known results. Here we prefer to deduce it from Proposition 1(a), since the same idea also applies to Proposition 4 below.

Proposition 3. The pair $(p, t)$ is irregular if and only if $S_3 \equiv S_6 \equiv 0 \pmod{p}$.

Proof. If $t = 2$, both statements are false. Assume that $t \neq 2$. By Proposition 1(a), $(p, t)$ is irregular if and only if $\sum_{a=1}^{p-1} a^{t} q_a \equiv 0 \pmod{p}$. Using the congruences
\[
q_{p-a} \equiv q_a + a^{-1}, \quad q_{p-2a} \equiv q_{2a} + (2a)^{-1}, \quad q_{2a} \equiv q_2 + q_a \pmod{p}
\]
and noting that $\sum_{a=1}^{m} a' \equiv 0 \pmod{p}$, we reformulate the last sum in two ways:
\[
\sum_{a=1}^{p-1} a^{t} q_a \equiv 2 \sum_{a=1}^{m} a^{t} q_a + \sum_{a=1}^{m} a^{t-1} \pmod{p},
\]
\[
\sum_{a=1}^{p-1} a^{t} q_a \equiv 2^{t+1} \sum_{a=1}^{m} a^{t} q_a + 2^{t-1} \sum_{a=1}^{m} a^{t-1} \pmod{p}.
\]
This gives us the claim. □

As mentioned in §3, we used this proposition to check that the pairs $(p, t)$ in the table by Tanner and Wagstaff are irregular.

Proposition 4. If $(p, t)$ is an irregular pair, then
\[
(1 - 2^t) \sum_{a=1}^{p-1} a^{t} q_a^2 \equiv -2^t S_1 \pmod{p},
\]
\[
(1 - 2^{t-1}) \sum_{a=1}^{p-1} a^{t} q_a^2 \equiv 2^t S_2 \pmod{p}.
\]

Proof. Reformulate the sum $\sum_{a=1}^{p-1} a^{t} q_a^2$ by the same principles as before. In view of $S_3 \equiv S_6 \equiv 0$ and $\sum_{a=1}^{m} a^{t-2} \equiv 0 \pmod{p}$ it follows that
\[
\sum_{a=1}^{p-1} a^{t} q_a^2 \equiv 2S_2 + 2S_1 \pmod{p},
\]
\[
\sum_{a=1}^{p-1} a^{t} q_a^2 \equiv 2^{t+1} S_2 + 2^t S_1 \pmod{p}.
\]
This pair of congruences yields the asserted congruences. □
By combining Propositions 2 and 4 we obtain the following formulas for
\[ \Delta = \frac{B_{t+p-1}}{t+p-1} - \frac{B_t}{t}, \]
provided \((p, t)\) is an irregular pair:
\[ (1 - 2^t)^{\frac{1}{p}} \Delta \equiv 2^{t-1} S_1, \quad (1 - 2^{t-1})^p \Delta \equiv -2^{t-1} S_2 \pmod{p}. \]

This proves Criteria 1 and 2.

**Remark.** The former of these congruences also follows from a result of E. Lehmer [7, p. 355]. She traces the congruence back to Mirimanoff.

**Proposition 5.** Excluding the case \( t = 2 \), we have
\[ (a) \quad (2^t - 1) \frac{B_t}{t} \equiv -2^{t-1} S_3 \pmod{p^2}, \]
\[ (b) \quad (3^t - 1) \frac{B_t}{t} \equiv -2 \cdot 3^{t-1} S_4 + 2 \cdot 3^{t-2} (1 - t) p S_5 \pmod{p^2}. \]

**Proof.** We look at Proposition 1(b) with \( b = 2 \) and \( 3 \), respectively. For \( b = 2 \) note that
\[ \sum_{a=1}^{p-1} a^{t-2} \equiv \sum_{a=m+1}^{p-1} a^{t-2} \equiv 0 \pmod{p} \]
and so, in particular,
\[ \sum_{a=1}^{p-1} a^{t-1} \equiv \sum_{a=1}^{m} (p - a)^{t-1} \equiv -S_3 \pmod{p^2}. \]
For \( b = 3 \) somewhat more lengthy calculations yield
\[ \sum_{a=1}^{p-1} a^{t-1} \left[ \frac{3a}{p} \right] \equiv -2 \sum_{0 < a < p/3} a^{t-1} - (t - 1)p \sum_{p/3 < a < p/2} a^{t-2} \pmod{p^2}, \]
\[ \sum_{a=1}^{p-1} a^{t-2} \left[ \frac{3a}{p} \right] \equiv -2 \sum_{p/3 < a < p/2} a^{t-2} \pmod{p}. \]

Substitute the right-hand sides in the congruence of Proposition 1(b) and simplify. □

Proposition 5 provides us the latter parts of Criteria 3 and 4.

**Proposition 6.** Excluding the case \( t = 2 \), we have
\[ B_1(\omega^{t-1}) \equiv \frac{B_t}{t} - \frac{t - 1}{2} p \sum_{a=1}^{p-1} a^t q_a^2 \pmod{p^2}. \]

**Proof.** We may write
\[ B_1(\omega^{t-1}) = \frac{1}{p} \sum_{a=1}^{p-1} (a + v_a p)^{t-1} a. \]
Since \( \frac{1}{p} \sum_{a=1}^{p-1} a^t \equiv B_t \pmod{p^2} \), this implies

\[
B_1(\omega^{t-1}) \equiv B_t + (t-1) \sum_{a=1}^{p-1} a^{t-1} v_a + \frac{(t-1)(t-2)}{2} p \sum_{a=1}^{p-1} a^{t-2} v_a^2 \pmod{p^2}.
\]

Multiply the congruence in Proposition 1(a) by \( t - 1 \) and add to this congruence. \( \square \)

**Proposition 7.** Let \((p, t)\) be an irregular pair. Then

\[
\frac{2^t - 1}{2^{t-1}} B_1(\omega^{t-1}) \equiv -S_3 + (1-t)pS_1 \pmod{p^3}
\]

and, provided that \( 2^{t-1} \not\equiv 1 \pmod{p} \),

\[
\frac{3^t - 1}{2 \cdot 3^{t-2}} B_1(\omega^{t-1}) \equiv -3S_4 + (1-t)pS_3
\]

\[
- \left( \frac{2}{3} \right)^{t-2} \frac{3^t - 1}{2^{t-1} - 1} (1-t)pS_2 \pmod{p^2}.
\]

**Proof.** These two results are verified by multiplying the congruence of Proposition 6 by \( 2^t - 1 \) or \( 3^t - 1 \), respectively, and then using Propositions 5(a) and 4(a), or 5(b) and 4(b), respectively. \( \square \)

This completes the proof of Criteria 3 and 4.

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**BIBLIOGRAPHY**