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Table of the Cyclotomic Class Numbers $h^*(p)$ and Their Factors for $200 < p < 521$

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Abstract. This table gives the values of the "first factor" $h^*(p)$ and their factorizations for all primes p, $200 < p < 521$. This extends similar data by M. Newman [*Math. Comp.*, v. 24, 1970, pp. 215–219], and Schrutka [*Berlin Akad. Abn.*, 1964]. The two methods used to compute these data are described.

1. Introduction. The present table extends a similar one given by Newman [8], for $p < 200$, in 1970. At that time Newman was unaware of a larger table by Schrutka [10] containing $h^*(p)$ and its factors for $p \leqslant 257$. In setting the range $200 < p < 521$ the authors decided to include the nine primes between 200 and 257 because Schrutka's table is incomplete as to some factorizations and also because his table is unavailable in most libraries. The present table appears in the microfiche section.

Two methods were used to obtain the results given herewith. The first method, an elaboration of Newman's, gives the value of $h^*(p)$ by a determinant. The second method obtains $h^*(p)$ as a product of its "algebraic" factors which in turn have their factors so strongly restricted that many quite large values of $h^*(p)$ have been completely factored. This factorization theory has been set forth in two other papers (Lehmer [5] and Masley [6]) from different points of view. This second method is more expensive than the first and, for $p > 300$, was used only to get all but the largest factor of $h^*(p)$, the latter being obtained from the value of $h^*(p)$ as given by the first method.

2. First Method. This method uses modular arithmetic to evaluate $h^*(p)$ from the formula

$$h^*(p) = |\det M|,$$

where M is the 0-1 matrix of order $(p-5)/2$

$$M = \{m_{rc}\} \qquad (r, c = 3(1)(p-1)/2)$$

with

$$m_{rc} = \left[\frac{rc}{p}\right] - \left[\frac{(r-1)c}{p}\right].$$

This formula was first published by Carlitz and Olson [1] as a consequence of their work on Maillet's determinant. A direct derivation is given in [6].

Before resorting to congruential computation it is advantageous to reduce M by elementary row and column operations to a much smaller matrix B. This reduction is aided by the fact that M is relatively sparse, having almost 75% of its entries zero,

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and the fact that the ones in M in column c are situated in rows

$$r = \left[\frac{(i-2)p}{c}\right] + 1 \qquad (i = 3(1)[(c-1)/2]).$$

Some of this reduction can be done for a general p. In fact, one may cross out columns 3, 4, 6 and rows $[p/6] + 1$, $[p/4] + 1$, and $[p/3] + 1$, thus reducing M to a 0-1 matrix of order $(p - 11)/2$. Further reductions depending on the form of p can be automated. For the range $200 < p < 521$ the matrix M was reduced to a matrix B of order k with $p/5 < k < p/3$ without any element of B exceeding 10^6 in absolute value. This preliminary reduction can be compared with that used by Newman [8] whose B is of order $(p - 1)/2$ with mostly nonzero entries less than p in absolute value. To compute det B use was made of modular arithmetic. Remainders r_i were found for which

$$\det B \equiv r_i \pmod{q_i} \qquad (i = 1(1)t)$$

and then combined by the Chinese remainder theorem to determine the actual value of det B. The q_i were chosen to be primes slightly greater than 10^9, and the process is valid provided

$$|\det B| < q_1 q_2 \cdots q_t. \tag{1}$$

To make an efficient choice of t it is essential to know quantitative upper bounds for $|\det B| = h^*(p)$. Fortunately, these have recently become available. Kummer [2] asserted that $h^*(p)$ is asymptotic to the function

$$G(p) = 2p(p/4\pi^2)^{(p-1)/4}. \tag{2}$$

This has not yet been proved. The best result to date in this direction is due to Lepistö [3] who proves that for $p > 200$,

$$-\tfrac{1}{2}\log p - 4\log\log p - 12.93 - 4.66/\log p$$
$$\leqslant \log(h^*(p)/G(p)) \leqslant 5\log\log p + 15.49 + 4.66/\log p.$$

These results can be improved by methods used in [6] but not enough to yield Kummer's conjecture. For the range $200 < p < 521$ the best known upper bound is

$$\log(h^*(p)/G(p)) \leqslant \log p + \log\log(p/3) + 3.52. \tag{3}$$

The number t of moduli was chosen using (2) and (3) so that at most one modulus was "wasted" in satisfying (1).

Every value of $h^*(p)$ obtained by this method was later compared with the table of approximations to $h^*(p)$ given in Pajunen [9]. These values were also subjected to stringent divisibility conditions imposed by the second method. Newman's results for $p < 200$ were recomputed in 90 seconds, as opposed to 30 minutes by Newman's method, and no discrepancy was found.

3. Second Method. This method is based on a norming procedure as applied to the fundamental factorization formula

$$h^*(p) = \prod_{ef=p-1;\, f \text{ odd}} h_e(p). \tag{4}$$

The positive integer $h_e(p)$, called the relative class number of degree e, is given by

(5) $$h_e(p) = p^{[e/(p-1)]} N_e(W_e(p))/Q_\tau(2)^\gamma.$$

Here

$$\tau = \tau(e) = \frac{e}{(e, \operatorname{ind}_g 2)},$$

where g is any primitive root of p. $Q_\tau(x)$ is the monic polynomial of degree $\phi(\tau)$ whose roots are the primitive τth roots of unity and

$$\gamma = \gamma(e) = \phi(e)/\phi(\tau).$$

Finally,

$$W_e(p) = \sum_{n=1}^{(p-1)/2} (\epsilon_n - \epsilon_{n-1})\alpha^n,$$

where $\alpha = \exp\{2\pi i/e\}$,

$$\epsilon_n = \begin{cases} 1 & \text{if } g^n - p[g^n/p] < p/2, \\ 0 & \text{otherwise;} \end{cases}$$

and $N_e(W_e(p))$ is the norm of $W_e(p)$ in the cyclotomic field of eth roots of unity.

This elaborate and relatively expensive formula is effective in factoring $h^*(p)$. Furthermore, it is shown in [5] and [6] that if

$$h_e(p) = q_1 q_2 \cdots q_t$$

is the canonical factorization of $h_e(p)$ into a product of distinct prime powers q_i ($i = 1(1)t$) then each q_i prime to e is of the form $ex + 1$, a valuable condition for several methods of factorization.

In (5) the function $Q_\tau(2)$ is readily evaluated by

$$Q_\tau(2) = \prod_{\delta \mid \tau} (2^\delta - 1)^{\mu(\tau/\delta)},$$

where μ is the Möbius function. Thus, the real expense of this method is that of the calculation of the norm

(6) $$N_e(W_e(p)) = \prod_{(t,e)=1;\, t<e} \left\{ \sum_{n=1}^{p-1} (\epsilon_n - \epsilon_{n-1})\alpha^{nt} \right\} = \prod_{(t,e)=1} W_e(p, t).$$

Metsankyla [7] has suggested a straightforward approach via multiprecise approximation of each factor of (6) using floating-point arithmetic followed by the recognition of the huge integer N_e. Instead, it was decided to follow a suggestion of Spira [11] and use a vector manipulation method with exact fixed point multiprecision arithmetic.

We begin the norming program by determining the coefficients

$$A_n = \epsilon_n - \epsilon_{n-1} = \pm 1, 0$$

of $W_e(p, 1)$ in a prelude to the main routine which generates a table of powers of a primitive root g (mod p). We can then think of $W_e(p, 1)$ simply as a vector of dimension $(p-1)/2$

$$W_e(p, 1) \sim [A_1, A_2, \ldots, A_{(p-1)/2}].$$

Since

$$\alpha^{n+e} = \alpha^n, \qquad \alpha^{r+e/2} = -\alpha^r,$$

this vector can be compressed to one of dimension $e' = e/2$

(7) $$W_e(p, 1) \sim [a_1, a_2, \ldots, a_{e'}],$$

where the a's are small integers. The corresponding vectors for the other factors $W_e(p, t)$ have the same set of components but in a different order.

To compute $N_e(W_e(p))$ we multiply the several vectors together in the Cauchy sense. Thus, in multiplying (7) by any other vector

$$[b_1, b_2, \ldots, b_{e'}]$$

we first obtain a vector

$$[c_1, c_2, \ldots, c_e]$$

of dimension e with

$$c_n = \sum_{i+j=n} a_i b_j \qquad (n = 1(1)e).$$

This is then compressed into a vector of dimension e' by replacing c_n by $c_n - c_{n+e'}$ for $n = 1(1)e'$. (In case $e = p - 1$ this whole procedure involves only addition and subtraction since $a_i = A_i = \pm 1, 0$.) Accumulating factors in this way, we obtain a vector representing the product of the first $\phi(e)/2$ factors in (6). Since the factors for t and $e - t$ are complex conjugates, the vector for the second half-product has the same components as those of the first but in reverse order. Multiplying these two vectors together, we obtain a vector for $N_e(W_e(p))$

$$[C_1, C_2, \ldots, C_e]$$

with large integer components. To find the integer thus represented we change notation slightly, replacing C_i by $f(i-1)$, and write

$$N_e(W_e(p)) = f(0) + f(1)\alpha + \cdots + f(e-1)\alpha^{e-1}.$$

Let δ be any divisor of e and let $e = e_1\delta$. If t_i $(i = 1(1)\phi(e_1))$ are the numbers $\leqslant e_1$ and relatively prime to e_1, then $\alpha^{\delta t_i}$ are the primitive e_1th roots of unity and their sum is $\mu(e_1)$. Since they are algebraically indistinguishable, their corresponding coefficients $f(\delta t_i)$ must be equal and equal to $f(\delta)$. Hence, we have

$$N_e(W_e(p)) = f(0) + \sum_{\delta | e} \mu(e_1) f(\delta) = f(0) + \sum_{\delta | e} \mu(\delta) f(e/\delta),$$

a formula that is easily programmed.

5. Irregular Primes. Kummer called a prime p irregular in case p divides a Bernoulli number B_{2a} with $2a < p$. Of the 51 primes in the range of our table 20 are irregular. As a result of a recent paper by Ribet [12], it follows that $p \mid h_e(p)$ where

$e = (p-1)/(p-1, 2a-1)$. This affords a welcome check on the computed value of $h_e(p)$. The following table lists these cases.

p	$2a$	e	p	$2a$	e
233	84	232	389	200	388
257	164	256	401	382	400
263	100	262	409	126	408
271	84	270	421	240	420
283	20	282	433	366	432
293	156	292	461	196	92
307	88	102	463	130	154
311	292	310	467	94	466
347	280	346	467	194	466
353	186	352	491	292	490
353	300	352	491	336	98
379	100	42	491	338	490
379	174	378			

The evidence in the main table supports the conjecture that the product $B_2B_4 \ldots B_{p-}$ and $h^*(p)$ contain p to the same highest power.

6. Description of the Tables. Table 1 gives for each of the 51 indented entries p with $200 < p < 521$ the value of the first factor $h^*(p)$ of the cyclotomic class number of $Q(\exp\{2\pi i/p\})$. This table and the next appear in the microfiche section of this issue.

Table 2 gives the factorizations of the entries in Table 1 as given by (4); one line is devoted to each $h_e(p)$. The first entry in each line is e itself. Each unmarked factor is a prime. If a factor is followed by * it is intrinsic, i.e. all of its prime factors divide e. If a factor is followed by # the factor is a power of a prime, q^α, $\alpha > 1$, such that e divides $q^\alpha - 1$. For example, for $p = 313$, $e = 24$, the entry 1369# is 37^2 and $1368 = 24 \cdot 57$. Oversize entries are put in two Appendices in order of size. The first of these is for primes designated by P followed by the number of its digits; a number greater than 37. The second Appendix is for composite numbers designated by C. For each of these numbers a space is left in the main Table 2 for writing in whatever factors may be discovered in the future. All such prime power factors are known to exceed 10^{11}.

The following procedures were followed in preparing Table 2. As soon as $h^*(p)$ was computed by the first method it was searched for factors less than 10^5 to discover all its intrinsic factors and the factors that are powers of small primes. The residual factor N was next tested for pseudo-primality by seeing whether

$$13^N \equiv 13 \pmod{N}. \tag{8}$$

If (8) fails to hold, N is composite and all its extrinsic prime power factors are of the form $ex + 1$. In this case a search for small factors of N was made using the Illiac IV which makes 64 trial divisions simultaneously, up to the limit 10^{11}. After removing such factors, if any, from N and applying (8) to the residual factor, a more serious attempt at factorization was made. For numbers up to 30 digits the Delay Line Sieve was used and for numbers up to 38 digits the Pollard Rho method and, if necessary, the Brillhart-Morrison method were applied by M. Wunderlich of the Northern Illinois University. As a result, we can say of the 26 composite numbers in the appendix that none has a prime factor $< 10^5$ and if any prime factor exists between 10^5 and 10^{11} its square must also be a factor. Any pseudoprimes discovered were sent to H. S. Williams at the University of Manitoba, who carried out the final tests for primality in all cases.

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TABLE OF FACTORS OF CYCLOTOMIC CLASS NUMBERS FOR PRIMES LESS THAN 512

3	
2	1

5	
4	1

7	
2	1
6	1

11	
2	1
10	1

13	
4	1
12	1

17	
16	1

19	
2	1
6	1
18	1

23	
2	3
22	1

29	
4	1
28	8*

31	
2	3
6	3*
10	1
30	1

37	
4	1
12	1
36	37

41	
8	1
40	121*

43	
2	1
6	1

```
14  1
42  211

  47
 2  5
46  139

  53
 4  1
52  4889

  59
 2  3
58  59.233

  61
 4  1
12  1
20  41
60  1861

  67
 2  1
 6  1
22  67
66  12739

  71
 2  7
10  1
14  74
70  79241

  73
 8  89
24  1
72  134353

  79
 2  5
 6  1
26  53
78  377911

  83
 2  3
82  279405653

  89
 8  113
88  118401449

  97
32  3457
96  577.206209
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```
  101
  4  5
 20  25*
100  25*.101.601.18701

  103
  2  5
  6  1
 34  1021
102  103.17247691

  107
  2  3
106  743.9859.2886593

  109
  4  17
 12  1
 36  1009
108  9431866153

  113
 16  17

112  8*.11853470598257

  127
  2  5
  6  13
 14  43
 18  3079
 42  547
126  883.626599

  131
  2  5
 10  5*
 26  27#.53
130  131.1301.4673706701

  137
  8  17
136  17*.47737.46890540621121

  139
  2  3
  6  3*
 46  47.47.277
138  277.967.1188961909

  149
  4  9#
148  149.51296633832004080546 1

  151
  2  7
```

```
  6  1
 10  281
 30  121*
 50  25951
150  1207501.312885301

  157
  4  5
 12  13
 52  3148601
156  13*.157.157.1093.1873.418861

  163
  2  1
  6  4*
 18  181
 54  365473
162  23167.441845817162679

  167
  2  11
166  499.51231899854842290359474l9

  173
  4  5
172  20297.231169.72571729362851870621

  179
  2  5
178  1069.14458667392334948286764635121

  181
  4  5.5
 12  37
 20  5*.41
 36  2521
 60  61.1321
180  54884357825892777 01

  191
  2  13
 10  11
 38  51263
190  612771091.3673395066973371 3761

  193
 64  192026280449
192  6529.15361.29761.91969.10369729

  197
  4  5
 28  8*.1877
196  7841.93983026848708666562256115 49

  199
  2  3.3
```

5.

```
  6  3*
 18  3*.19
 22  727
 66  25645093
198  207293548177.3168190412839

 211
  2  3
  6  3*.7
 10  41
 14  281
 30  181
 42  7*.421
 70  71.281.12251
210  1051.113981701.4343510221

 223
  2  7
  6  43
 74  17909933575379
222  11757537731851.3424804483726447

 227
  2  5
226  2939.2939.2939.1692824021974901.13444015915122722869

 229
  4  17
 12  13
 76  705053.47824141
228  457.7753.414153903321692666991589

 233
  8  1433
232  233.

 239
  2  3.5
 14  64*
 34  511123
238  14136487.123373184789.22497399987891136953079

 241
 16  2209*
 48  2359873
 80  15601.126767281
240  13921.518123008737871423891201

 251
  2  7
 10  11
 50  348270001
250  9631365977251.369631114567755437243663626501

 257
256  257.20738946049.P43
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C43

6.

```
  263
  2  13
262  263.787.385927.P45

  269
  4  13
268  40170973189.                                                  C46

  271
  2  11
  6  1
 10  31
 18  37
 30  1201
 54  751928131
 90  21961.7288651
270  271.811.1621.15391.20238391.666587726641

  277
  4  17
 12  16*
 92  89977.1371353.30697273
276  829.2209*.4873333.177683490924471681107248б129

  281
  8  17
 40  41.41.121*.401
 56  64523056921
280  3235961.97734313997623396856946107541140б081

  283
  2  3
  6  3*
 94  2064523.39341481709417
282  283.P40

  293
  4  9*
292  293.38901409.52561753.354041533.19844792749.702405569982494626097540798З3

  307
  2  3
  6  3*
 18  3*.37
 34  137.443.1429
102  307.10191268178209
306  613.919.51241244102964847989776639133916589З563

  311
  2  19
 10  41
 62  1024*.9918966461
310  311.P54

  313
```

```
  8  233
 24  1369#
104  65386361.30358065621833
312  155288017.82941207961.98668596378200960391968095З

  317
  4  13
316                                                    C74

  331
  2  3
  6  9*
 10  81#
 22  23.67
 30  81*.61
 66  17406850561
110  4765069732417846673 81
330  270271.221475181712309125848473872740271

  337
 16  17.17.49#.353
 48  238321
112  49*.894469355265098929
336  64*.3246769.                                      C41

  347
  2  5
346  347.P82

  349
  4  5
 12  16*.13
116  421081.943429.2021708236660033
348  2089.17749.29247661.P41

  353
 32  6113.9473
352  353.353.281249.1380c11233.3001891553.P50

  359
  2  19
358                                                    C88

  367
  2  3.3
  6  3*
122  733.268738874461290742168853881
366  39163.P57

  373
  4  5
 12  61
124  32*.1117.6218451821.1699148567515153
372  1489.191953.P54

  379
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```
  2  3
  6  3*.13
 14  1499
 18  3*.991
 42  379.547
 54  3*.29997973
126  127.757.9199.154412119
378  379.1087873417.                                   C45

  383
  2  17
382  300032351.                                        C88

  389
  4  41
388  389.1553.4847366257.                              C83

  397
  4  13
 12  64*
 36  109.4861
 44  23910808769
132  529*.132189553.1917436489
396  9901.                                             C59

  401
 16  64849
 80  1681*.476056112401
400  401.462972001.3692494801.                         C64

  409
  8  17.25*
 24  73.1321
136  17*.122181721.7960379881.29097077764969
408  409.                                              C64

  419
  2  3.3
 22  647747
 38  1103.5410099
418                                                    C94

  421
  4  5.5
 12  37
 20  5*.2521
 28  29.39509
 60  16*.22064701
 84  70309.46085341
140  672896721281.6770213592521
420  421.39901.3455761.57979841174101.26555795167513314099108 61

  431
  2  3.7
 10  11.701
 86  676649.2709472364809333
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430  14621.7470051.P78

  433
 16  842353
 48  4727329
144  3457.302156474234870153721 7
432  433.12097.21601.47521.1403137.102550753.                C48

  439
  2  3.5
  6  27*
146  293.527207.7171667.50898521.327151064937209
438                                                          C78

  443
  2  5
 26  27*.27*.79.157
 34  367926037
442  12377.2099059.P93

  449
 64  500402969557121
448  168449.                                                 C102

  457
  8  41
 24  25*.577
152  1217.43777.2335315267744322364825726849633 7
456  63841.P75

  461
  4  5.5
 20  25*.661
 92  461.4634132613466743 97069
460  161461.P92

  463
  2  7
  6  7
 14  56*.29
 22  89.1123
 42  7*.631.673
 66  4423.33642841
154  463.6640642078185946092575393272 51
462  8779.                                                   C63

  467
  2  7
466  467.467.                                                C128

  479
  2  5.5
478  48757.62141.2560169.                                    C116

  487
  2  7
```

```
  6  7
 18  37.37
 54  919.2647.10909
162  105792786991.1355141213869532941
486  58321.105290443.                                              C79

  491
  2  3.3
 10  11.11.11
 14  64*.29
 70  1262296191031
 98  491.101566319.2311247713517
490  491.491.8489251.17841391.74468731.P68

  499
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PRIMES AND PSEUDOPRIMES

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 P 45  263 262
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 P 50  353 352
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P 78 431 430
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COMPOSITE COFACTORS

C 41 337 336
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C 43 233 232
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C 45 379 378
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C 46 269 268
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C 48 433 432
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C 59 397 396
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C 63 463 462
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C 64 401 400
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C 64 409 408
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C 74 317 316
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C144 509 508
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249