On Conjugacy Classes of Groups of Squarefree Order

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Abstract

The problem of finding the largest finite group with a certain class number (number of conjugacy classes), $k(G)$, has been investigated by a number of researchers since the early 1900's and has been solved by computer for $k(G) \leq 9$. (For the restriction to simple groups for $k(G) \leq 12$.) One has also tried to find a general upper bound on $|G|$ in terms of $k(G)$. The best known upper bound in the general case is in the order of magnitude $|G| \leq k(G)^{2^{k(G)-1}}$. In this paper we consider the restriction of this longstanding problem to groups of squarefree order. We derive an explicit formula for the class number $k(G)$ of any group of squarefree order and we also obtain an estimate $|G| \leq k(G)^3$ in this case. Combining the two results we get an efficient way to compute the largest squarefree order a group with a certain class number can have. We also provide an implementation of this algorithm to compute the maximal squarefree $|G|$ for arbitrary $k(G)$ and display the results obtained for $k(G) \leq 100$.

1 Introduction

Conjugacy classes are a vital tool in the analysis of groups. A condensed piece of information about a group is its class number, that is its number of conjugacy classes. Starting with small numbers mathematicians have tried to catalogise all groups having a given class number. A very brief history of this problem with references can be found in [5]. The starting point was when Landau in 1903 managed to show that there is only a finite number of non-isomorphic finite groups with class number k, and also derived an upper bound on the group size as a function of k. In [5] Poland extends the complete list of groups with class number k from $k \leq 5$ to $k \leq 7$. Using computerised methods this was later pushed forward to cover $k \leq 9$ (references can be found in [2]) and considering only simple groups further to $k \leq 12$ by Komissarcik in [2]. The reason to limit the search to simple groups was that for $5 \leq k \leq 9$ the largest groups with a given class number are all simple. Hence one might guess that this is true also for larger k even though this seems to be unknown.

There has also been successful attempts to attack other types of groups. For example p-groups where it is known that a group of order p^m has $(n+r(p-1))(p^2-1)+p^e$ conjugacy classes where r is some non-negative integer and $m = 2n + e$, $e = 0$ or 1 depending on the parity of m. This result can be found in [6].

In this paper we will go in the opposite direction and instead of p-groups consider groups of squarefree order. We will derive an explicit formula for the class numbers groups of a given squarefree order can have. As a by product of the analysis we will also see that a group of squarefree order having k conjugacy classes can have no more than k^3 elements. As mentioned there are bounds on the group order in the general case, but in contrast to this bound they are far from sharp.

It is of course a substantial confinement to consider only groups of squarefree orders. It should be noted however that most group orders are covered, as $\lim_{n\to\infty} \frac{Q(n)}{n} = \frac{6}{\pi^2}$, where $Q(n)$ denotes the number of squarefree numbers $\leq n$. (See [1].) In addition the techniques developed here can hopefully be modified in order to cover other types of groups which have relatively simple presentations.

2 Description of the conjugacy classes

In this section we will describe the conjugacy classes of groups of squarefree order. Along the way we will also introduce some notation that will be used throughout this article.

Let G be a group of squarefree order n. Then Murty and Murty ([3]) have proven that G has a presentation of the form

$$\langle x, y | x^d = id, y^e = id, x^{-1}yx = y^t \rangle \tag{1}$$

for some divisor d of n, $e = n/d$ and some integer t which is of order d modulo e. We will use this presentation to compute the conjugacy classes of G.

Remark 1 *Note that an element t of order d modulo e exists only for those factorisations $n = d \cdot e$ which satisfy $(d, \phi(e)) = d$. This is since $(d, \phi(e)) = d' < d$ implies $t^{d'} \equiv t^{ad+b\phi(e)} \equiv 1$ contradicting that t is order d.*

Proposition 2 *Let G be a group of squarefree order $n = de$ and*

$$\langle x, y | x^d, y^e, x^{-1}yx = y^t \rangle$$

a presentation of G. Then the size of the conjugacy class containing the element $x^a y^b$ is $k\frac{e}{(e,1-t^a)}$ where k is the smallest positive integer for which $b(t^k - 1) \equiv 0$ modulo $(e, 1 - t^a)$.

Proof: Any element of G has a unique representation $x^a y^b$ with $0 \leq a \leq d - 1$ and $0 \leq b \leq e - 1$ and a straightforward computation using the relations gives that

$$x^{-1}x^a y^b x = x^a y^{tb} \qquad \text{and} \qquad y^{-1}x^a y^b y = x^a y^{b+1-t^a}$$

This shows that elements of the form $x^a y^b$ can be conjugates only of elements of the form $x^a y^{b_1}$. Moreover these two elements are conjugate if and only if b_1 can be obtained from b by a sequence of the operations $O_1 : b \mapsto tb$ and $O_2 : b \mapsto b + 1 - t^a$. Let S_b be the set obtained from the element b in this way. The size of S_b equals the size of the conjugacy class containing $x^a y^b$ so we would like to compute $|S_b|$. In fact we can describe the set S_b in the following way: Let k be the smallest positive integer such that

$$b(t^k - 1) \equiv s(1 - t^a) \bmod e$$

for some integer s. Note that such a k exists and is at most a since for $k = a$ we may take $s = -b$. Now we will show that

$$S_b = \{t^r b + s(1 - t^a) | 0 \leq r \leq k - 1, s \in \mathbb{Z}\}$$

We regard S_b as a subset of $\mathbb{Z}_e$ as it is only the residue modulo e that affects which element $x^a y^b$ we get in G. It is clear that an arbitrary element $t^r b + s(1 - t^a)$ in

$$M_b = \{t^r b + s(1 - t^a) | 0 \leq r \leq k - 1, s \in \mathbb{Z}\}$$

can be obtained from b simply by first applying $b \mapsto tb$ r times and then $b \mapsto b + 1 - t^a$ s times. Thus it is clear that $M_b \subseteq S_b$. On the other hand M_b contains b and it is straightforward to check that it is closed under the two operations O_1 and O_2. Hence we must have $M_b = S_b$. Also two elements in

$$S_b = \{t^r b + s(1 - t^a) | 0 \leq r \leq k - 1, s \in \mathbb{Z}\} \subseteq \mathbb{Z}_e$$

are different $t^{r_1} b + s_1(1 - t^a) \not\equiv t^r b + s(1 - t^a) \bmod e$ exactly when $s \not\equiv s_1$ modulo $\frac{e}{(e, 1-t^a)}$ since if we have

$$t^r b + s(1 - t^a) \equiv t^{r_1} b + s_1(1 - t^a) \bmod e$$

with $0 \leq r_1 \leq r \leq k - 1$ then $t_1^r(b - t^{r-r_1} b) \equiv (s - s_1)(1 - t^a)$ and as t is order d mod e t is invertible and we get $(b - t^{r-r_1} b) \equiv t_1^{-r}(s - s_1)(1 - t^a)$. From the definition of k it follows that $r - r_1 \geq k$ unless $r = r_1$ so considering the condition $0 \leq r_1 \leq r \leq k - 1$ the numbers r and r_1 must be equal. It follows that $s(1 - t^a) \equiv s_1(1 - t^a)$ modulo e and this holds if and only if $s \equiv s_1$ modulo $\frac{e}{(e, 1-t^a)}$. This shows that there are $k \frac{e}{(e, 1-t^a)}$ different elements in the set S_b.

The proposition now follows by noting that there is an integer s with

$$b(t^k - 1) \equiv s(1 - t^a) \bmod e$$

if and only if $b(t^k - 1) \equiv 0$ modulo $(e, 1 - t^a)$.

♦

In the following we shall use the smallest common divisors $(e, 1 - t^s)$ frequently and therefore we introduce the notation $\alpha_s = (e, 1 - t^s)$ for $1 \leq s \leq d$.

As a consequence of the above proposition we get a lower bound on the number of conjugacy classes of a group of squarefree order.

Theorem 3 *Let G be a group of squarefree order and $k(G)$ the number of conjugacy classes of G. Then $|G| \leq k(G)^3$.*

Proof: Let $n = de$ be any factorisation of $n = |G|$. By the above proposition we know that any conjugacy class containing an element $x^a y^b$ has $k\frac{e}{\alpha_a}$ elements for some k between 1 and d. Thus, if we denote the class containing x by $C(x)$, $\frac{e}{\alpha_a} \leq |C(x^a y^b)| \leq d\frac{e}{\alpha_a}$. For a fixed a there are e elements to distribute among such classes and hence the resulting number of classes must be between $\frac{\alpha_a}{d}$ and α_a. Summing over all a we get $\frac{1}{d}\sum_{a=1}^{d} \alpha_a \leq k(G) \leq \sum_{a=1}^{d} \alpha_a$. Noting that $\alpha_d = (e, 1-t^d) = e$ we get $\frac{e}{d} \leq \frac{1}{d}\sum_{a=1}^{d} \alpha_a \leq k(G)$. On the other hand each a results in at least one class so $d \leq k(G)$. Taken together $|G| = n = de = \frac{e}{d}d^2 \leq k(G)^3$.
♦

Remark 4 *This bound does not hold for groups of arbitrary orders. In fact a smallest counter example is given by A_6, the alternating group on 6 symbols, which has 360 elements but only 7 conjugacy classes.*

This bound can be compared with the smallest bound known to hold for all groups which is in the order of magnitude $|G| \leq k(G)^{2^{k(G)-1}}$. (See [4].) There are however lower estimates for a number of specific types of groups.

3 A formula for the class number

Let us continue to compute the number of conjugacy classes for groups of squarefree order, which as we have seen always have some presentation of the form (1). Let us for the rest of this section assume that d, e and t are fixed, in other words that we are working with a fixed group and a certain presentation of it. We also assume that n is squarefree and hence that e can be written as a product $e = p_1 p_2 p_3 \cdots p_m$ of distinct primes. From Proposition 2 it is clear that the sizes of the conjugacy classes depend only on the sequence $\alpha = (\alpha_1, \alpha_2, \ldots, \alpha_d)$. On the other hand $\alpha_s = (e, 1-t^s)$ is a product of those primes p_i for which the order of t modulo p_i divides s. Hence α can be directly computed from the order of t modulo the divisors p_i of e. The fact that t is of order d modulo e restricts the possible orders modulo p_i to numbers dividing $(d, p_i - 1)$, but for any $d_i|(d, p_i - 1)$ there is a t with this order modulo p_i. From the Chinese Remainder Theorem it follows that for any sequence $\mathbf{d} = (d_1, d_2, \ldots, d_r)$ with $d_i|(d, p_i - 1)$ there is a t such that t has order d_i modulo p_i for each i. From the sequence $\mathbf{d}$ we now get the corresponding α-sequence by $\alpha_l = \prod_{d_i|l} p_i$. Let us for future use note two interesting properties of α that follows from this description:

Proposition 5 *Let e be a squarefree number and t a positive integer. The sequence $\alpha = (\alpha_1, \alpha_2, \ldots, \alpha_d)$ where $\alpha_s = (e, 1-t^s)$ then has the property that $(\alpha_k, \alpha_l) = \alpha_{(k,l)}$.*

Proof: As above we let d_i be the order of t modulo p_i and thus get the expression $\alpha_l = \prod_{d_i|l} p_i$ for α_l. It follows that

$$(\alpha_k, \alpha_l) = (\prod_{d_i|k} p_i, \prod_{d_i|l} p_i) = \prod_{d_i|(k,l)} p_i = \alpha_{(k,l)}$$

♦

Proposition 6 *Let e be a squarefree number and t some positive integer which is of order d modulo e. The sequence $\alpha = (\alpha_1, \alpha_2, \ldots, \alpha_d)$ where $\alpha_s = (e, 1 - t^s)$ then has the property that $\alpha_k = \alpha_{(k,d)}$.*

Proof: As before we know that $\alpha_l = \prod_{d_i|l} p_i$ where d_i is the order of t modulo e. Clearly we must have that $d_i|d$ since d is the order of t modulo $e = p_1 p_2 p_3 \cdots p_m$. It follows that $d_i|l$ if and only if $d_i|(l, d)$. Consequently

$$\alpha_l = \prod_{d_i|l} p_i = \prod_{d_i|(d,l)} p_i = \alpha_{(d,l)}$$

♦

Above we have constructed the sequence α for a given group of squarefree order $n = de$. Now we want to compute the number of conjugacy classes from the sequence α. By Proposition 2 we know that the size of the class containing $x^a y^b$ is $k \frac{e}{\alpha_a}$ and we observe that k is the smallest positive integer such that $b \equiv 0$ modulo $\frac{\alpha_a}{(\alpha_a, \alpha_k)}$. To count how many b we get for a certain value of k we introduce the following notation. Let

$$C_j = \{b \mid b \equiv 0 \quad \text{modulo} \quad \frac{\alpha_a}{(\alpha_a, \alpha_j)}\} \subseteq \mathbb{Z}_e$$

The elements $x^a y^b$ ending up in conjugacy classes of size $k \frac{e}{\alpha_a}$ are those where b is in the set $C_k \setminus \cup_{j=1}^{k-1} C_j$. From the principle of inclusion and exclusion we get an expression for the size of this set that can be used for computation.

$$|C_k \setminus \bigcup_{j=1}^{k-1} C_j| = |C_k| + \sum_{l=1}^{k-1} (-1)^l \sum_{j_1 < j_2 < \cdots < j_l < k} |C_k \cap \bigcap_{s=1}^{l} C_{j_s}|$$

Now from the definition of C_k and proposition 5 it follows that

$$|\bigcap_{s=1}^{t} C_{j_s}| = \frac{e(\alpha_a, \alpha_{j_1}, \alpha_{j_2}, \ldots, \alpha_{j_t})}{\alpha_a} = \frac{e\alpha_{(a, j_1, j_2 \ldots j_t)}}{\alpha_a}$$

and hence the above expression can be rewritten as

$$|C_k \setminus \bigcup_{j=1}^{k-1} C_j| = \frac{e}{\alpha_a}(\sum_{l=0}^{k-1}(-1)^l \sum_{j_1<j_2<\cdots<j_l<k} \alpha_{(a,k,j_1,j_2,\ldots,j_l)})$$

Now the above expression counts the number of elements in the group containing exactly a factors of x that belong to a conjugacy class of size $k\frac{e}{\alpha_a}$. We can now compute the total number of classes for fixed k:

$$\sum_{a=1}^{d}(\frac{1}{k}(\sum_{l=0}^{k-1}(-1)^l \sum_{j_1<j_2<\cdots<j_l<k} \alpha_{(a,k,j_1,j_2,\ldots,j_l)}))$$

Finally summation over all possible values of k results in a formula for the total number of conjugacy classes in the group:

$$k(G) = \sum_{k=1}^{d}\sum_{a=1}^{d}(\frac{1}{k}(\sum_{l=0}^{k-1}(-1)^l \sum_{j_1<j_2<\cdots<j_l<k} \alpha_{(a,k,j_1,j_2,\ldots,j_l)}))$$

The above formula is explicit but not very handy for computation. We therefore rewrite it into a form where all α_j are collected together.

Theorem 7 *Let $n = de$ be a squarefree number with $e = p_1p_2p_3\cdots p_m$ and G the group with presentation (1). Further, let d_i be the order of t modulo p_i and $\alpha_j = \prod_{d_i|j} p_i$. Then the class number of G equals*

$$k(G) = \sum_{k=1}^{d}\sum_{a=1}^{d}(\frac{1}{k}(\sum_{l=0}^{k-1}(-1)^l \sum_{j_1<j_2<\cdots<j_l<k} \alpha_{(d,a,k,j_1,j_2,\ldots,j_l)}) =$$

$$= d\sum_{j|d}\frac{\alpha_j}{j^2}\sum_{s|\frac{d}{j}}\frac{\mu(s)}{s^2} \qquad (2)$$

where μ denotes the Möbius function.

Remark 8 *The first expression for $k(G)$ is clear from the discussion above if we only note that it is legitimate to include d in the greatest common divisors by proposition 6. The reason for doing that is to simplify the formula by reducing the number of terms leaving only those α indices which are divisors of d.*

Proof: The proof is by induction on the indices of α. First we prove that for any d the coefficient of α_1 is equal on both sides of the equation.

Let $d = q_1q_2\ldots q_t$. First look at the inner sum of the LHS for a fixed pair (a,k). Let $(a,k,d) = q_1q_2\ldots q_s$ (where $s \leq t$). We are interested in the coefficient of α_1 so we should, for each l, count the number of sequences $(j_1, j_2, \ldots, j_l)$ with $(a,k,d,j_1,j_2,\ldots,j_l) = 1$. Now $(a,k,d,j_1,j_2,\ldots,j_l) = 1$ if and only if none of the primes $(a,k,d) = q_1q_2\ldots q_s$ divide every number in the sequence $(j_1, j_2, \ldots, j_l)$. Using the principle of inclusion and exclusion we can count the number of such sequences. Let $D_i = \{(j_1, j_2, \ldots, j_l) \mid q_i | j_r \text{ for } r = 1, 2, 3 \ldots, l\}$, the set of sequences divisible by q_i and $U = \{(j_1, j_2, \ldots, j_l)\}$, the set of all sequences. Then

$$|U \setminus \bigcup D_i| = |U| + \sum_{m=1}^{s} (-1)^m \sum_{1 \le i_1 < i_2 < \ldots < i_m \le s} |\bigcap_{r=1}^{m} D_{i_r}|$$

Noting that

$$|\bigcap_{r=1}^{m} D_{i_r}| = \binom{\frac{k}{q_{i_1} q_{i_2} \cdots q_{i_m}} - 1}{l}$$

as the elements of these sequences are chosen among the $\frac{k}{q_{i_1} q_{i_2} \cdots q_{i_m}} - 1$ numbers between 1 and $k-1$ that are divisible by $q_{i_1} q_{i_2} \cdots q_{i_m}$, we obtain

$$|U \setminus \bigcup D_i| = \binom{k-1}{l} + \sum_{m=1}^{s} (-1)^m \sum_{1 \le i_1 < i_2 < \ldots < i_m \le s} \binom{\frac{k}{q_{i_1} q_{i_2} \cdots q_{i_m}} - 1}{l}$$

We can now compute the coefficient of α_1 in the inner sum of the LHS of the proposition by summing over l thus obtaining

$$\sum_{l=0}^{k-1} (-1)^l \left(\binom{k-1}{l} + \sum_{m=1}^{s} (-1)^m \sum_{1 \le i_1 < i_2 < \ldots < i_m \le s} \binom{\frac{k}{q_{i_1} q_{i_2} \cdots q_{i_m}} - 1}{l} \right) =$$

$$= \sum_{m=1}^{s} (-1)^m \sum_{1 \le i_1 < i_2 < \ldots < i_m \le s} \sum_{l=0}^{k-1} (-1)^l \binom{\frac{k}{q_{i_1} q_{i_2} \cdots q_{i_m}} - 1}{l}$$

as the first sum vanishes by the binomial theorem. Here, again by the binomial theorem, the innermost sum is zero unless $k = q_{i_1} q_{i_2} \cdots q_{i_m}$ in which case the sum is 1. The second case can occur only for $m = s$ as $(a, k, d) = q_1 q_2 \ldots q_s$ and then the total sum is $(-1)^s$. Thus we have shown that the coefficient of α_1 in the inner sum of the LHS equals $(-1)^s$ if $k = q_1 q_2 \ldots q_s = (a, k, d)$ and zero otherwise so we get the coefficient of α_1 in the LHS as

$$\sum_{k=1}^{d} \sum_{a=1}^{d} \frac{1}{k} \left\{ \begin{array}{cc} (-1)^s & \text{if} \quad k = q_1 q_2 \ldots q_s \\ 0 & \text{otherwise} \end{array} \right\} =$$

$$= \sum_{k|d} \frac{\mu(k)}{k} \frac{d}{k}$$

and this is just the coefficient of α_1 in the RHS of the proposition. This completes the proof of the base for the induction.

Let us now move on to the induction step. We assume that the coefficient of α_k in the LHS and the RHS of the proposition are equal for each $k < j$ (for any d). We now want to show that the coefficients of α_j are equal on both sides. Let p be a prime that divides

j. We may assume that $p|d$ since otherwise the coefficient of α_j is obviously zero on both sides of the equality. Looking at the LHS_d of the proposition we find that studying the coefficient of α_j it is only interesting to sum over a and k divisible by p. Writing $d = pd'$, $a = pa'$, $k = pk'$, $j = pj'$ and $j_t = pj'_t$ we are looking for the coefficient of $\alpha_{pj'}$ in

$$\sum_{a'=1}^{d'} \sum_{k'=1}^{d'} \frac{1}{pk'} \sum_{l=0}^{pk'-1} (-1)^l \sum_{j'_1 < j'_2 < \cdots < j'_l < k'} \alpha_{p(a',k',d',j'_1,j'_2,\ldots,j'_l)}$$

Here the second last summation can just as well stop at $k' - 1$ since the last sum is empty for larger indices. Taking this into consideration and looking at the above formula we find that the coefficient of $\alpha_j = \alpha_{pj'}$ in LHS_d equals $\frac{1}{p}$ times the coefficient of $\alpha_{j'}$ in $LHS_{d'}$. On the other hand the latter equals $\frac{1}{p}$ times the coefficient of $\alpha_{j'}$ in $RHS_{d'}$ by the induction hypothesis. We would like to show that this in turn equals the coefficient of $\alpha_{pj'}$ in RHS_d so let us compare those coefficients. The last one is

$$\frac{pd'}{(pj')^2} \sum_{s|\frac{d}{j}} \frac{\mu(s)}{s^2} =$$

$$= \frac{d'}{pj'^2} \sum_{s|\frac{d'}{j'}} \frac{\mu(s)}{s^2}$$

which equals just$\frac{1}{p}$ times the coefficient of $\alpha_{j'}$ in $RHS_{d'}$. This completes the induction step and thus the proof of the theorem.

♦

4 Computation of class numbers

Using the class number formula above one can easily compute all possible class numbers for groups of a given squarefree order n. The algorithm was implemented in the computer algebra system Magma (see appendix).

The resulting class numbers for small group orders n are shown in Table 1.

Example: Let us, in order to better understand what the formula we have derived means and how it can be used, by hand compute the smallest class number that a group of order $n = 2 \cdot 3 \cdot 5 \cdot 7 = 210$ can have. We have to consider the different factorisations $n = de$ and in each case compute the smallest class number. It is not hard to see that the values in the α-sequence are minimal when the values in the d-sequence are maximal and that this occurs when $d_i = (d, p_i)$. (See the beginning of section 3 for the definition and basic properties of the d- and α-sequences.) This gives us the smallest class number for a given d. Moreover, not all factorisations $n = de$ need to be considered. Recall that the

Table 1: All class numbers a group of given squarefree order can have. Prime orders have been omitted to save space as the only possible class number in this case is the group order.

$\lvert G\rvert$	Smallest $k(G)$	All $k(G)$	$\lvert G\rvert$	Smallest $k(G)$	All $k(G)$
1	1	1	57	9	9, 57
6	3	3, 6	58	16	16, 58
10	4	4, 10	62	17	17, 62
14	5	5, 14	65	65	65
15	15	15	66	18	18, 21, 33, 66
21	5	5, 21	69	69	69
22	7	7, 22	70	19	19, 25, 28, 70
26	8	8, 26	74	20	20, 74
30	9	9, 12, 15, 30	77	77	77
33	33	33	78	8	8, 14, 21, 24, 39, 78
34	10	10, 34	82	22	22, 82
35	35	35	85	85	85
38	11	11, 38	86	23	23, 86
39	7	7, 39	87	87	87
42	7	7, 10, 12, 15, 21, 42	91	91	91
46	13	13, 46	93	13	13, 93
51	51	51	94	25	25, 94
55	7	7, 55	95	95	95

group for which our formula gives the class number has a presentation (1) where t is an integer which is of order d modulo e and that this implies that $d \mid \phi(e)$ by Remark 1.

In our case the divisors of n are $d = 1, 2, 3, 5, 7, 6, 10, 14, 15, 21, 35, 30, 42, 70, 105, 210$. Out of those only $d = 1, 2, 3, 6$ satisfy $(d, \phi(e)) = d$. The smallest class number of a group corresponding to a certain d can now be computed by determining first $d_i = (d, p_i)$ (where $e = \prod_{i=1}^{m} p_i$) and then $\alpha_j = \prod_{d_i|j} p_i$ which is substituted into (2). We may omit the computations for $d = 1$ as G is this case is cyclic and hence has class number $|G| = 210$.

For $d = 2$ we have $e = p_1p_2p_3 = 3 \cdot 5 \cdot 7$, and hence $d_1 = (d, p_1 - 1) = (2, 2) = 2, d_2 = (d, p_2 - 1) = (2, 4) = 2$ and $d_3 = (d, p_3) = (2, 6) = 2$ so $\mathbf{d} = (2, 2, 2)$. From this we get $\alpha_1 = \prod_{d_i|1} p_i = 1$ and $\alpha_2 = \prod_{d_i|2} p_i = 3 \cdot 5 \cdot 7 = 105$ so $\alpha = (1, 105)$. Now by formula (2) the class number is the dot product of α and $2(1 - \frac{1}{2^2}, \frac{1}{2^2}) = \frac{1}{2}(3, 1)$ so $k(G) = \frac{1}{2}(3, 1) \cdot (1, 105) = 54$

A similar computation for $d = 3$ gives $\mathbf{d} = (1, 1, 3)$, $\alpha = (10, 70)$ and $k(G) = 3(10, 70) \cdot (1 - \frac{1}{3^2}, \frac{1}{3^2}) = \frac{1}{3}(10, 70) \cdot (8, 1) = 50$.

Finally, for $d = 6$ we have $\mathbf{d} = (2, 6)$, $\alpha = (1, 5, 1, 35)$ and $k(G) = 6(1, 5, 1, 35)(1 - \frac{1}{2^2} - \frac{1}{3^2} + \frac{1}{2^2 3^2}, \frac{1}{2^2}(1 - \frac{1}{3^2}), \frac{1}{3^2}(1 - \frac{1}{2^2}), \frac{1}{2^2 3^2}) = \frac{1}{6}(1, 5, 1, 35) \cdot (24, 8, 3, 1) = 17$.

We have now computed the smallest class number for each choice of d and obtained $k(G) = 210, 54, 50, 17$ for $d = 1, 2, 3, 6$ respectively. We conclude that the smallest possible class number for a group of order 210 is 17 and that this occurs for the group with presentation

$$\langle x, y | x^6 = id, y^3 5 = id, x^{-1} y x = y^t \rangle$$

where t is a number of order 6 modulo 35, order 2 modulo 5 and order 6 modulo 7. There are two possible values, $t = 19, 24$, which give isomorphic groups.

♦

As the above example illustrates the problem when wanting to find the smallest class number that can occur for groups of a given order n is that we do not know in advance which factorisation $n = de$ will give the smallest class number. Thus we would like to know how to choose d to make the class number minimal. As long as the number of factors in n is small one can analyse all possibilities.

Let us see what happens if $n = pqr$ where $p < q < r$ are primes. The class number is determined from our formula once we have computed the α-sequence, and this sequence is in turn determined by the d-sequence. As we have noted we only have to consider the choice $d_i = (d, \phi(p_i))$, p_i being the ith factor in e, if searching for the smallest class number a group with presentation (1) can have. This means that all information we need about p, q and r is something that allows us to compute the d_i. This can be done if we know exactly which of the three conditions below are satisfied

- **A:** $p | q - 1$
- **B:** $p | r - 1$

Table 2: Class numbers for groups of order pqr. The capital letters in the leftmost column describes which of the conditions **A** :$p|q-1$, **B** :$p|r-1$ and **C** :$q|r-1$ are satisfied.

	$d=1$	$d=p$	$d=q$	$d=r$	$d=pq$	$d=pr$	$d=qr$	$d=pqr$
-	$\mathbf{pqr}$	-	-	-	-	-	-	-
A	pqr	$\mathbf{pr+\frac{r(q-1)}{p}}$	-	-	-	-	-	-
B	pqr	$\mathbf{pq+\frac{q(r-1)}{p}}$	-	-	-	-	-	-
C	pqr	-	$\mathbf{pq+\frac{p(r-1)}{q}}$	-	-	-	-	-
AB	pqr	$\mathbf{p+\frac{qr-1}{p}}$	-	-	-	-	-	-
AC	pqr	$pr+\frac{r(q-1)}{p}$	$\mathbf{pq+\frac{p(r-1)}{q}}$	-	-	-	-	-
BC	pqr	$pq+\frac{q(r-1)}{p}$	$pq+\frac{p(r-1)}{q}$	-	$\mathbf{pq+\frac{r-1}{pq}}$	-	-	-
ABC	pqr	$p+\frac{qr-1}{p}$	$pq+\frac{p(r-1)}{q}$	-	$\mathbf{pq+\frac{r-1}{pq}}$	-	-	-

- **C:** $q|r-1$

Considering all combinations of factorisations $n = de$ and conditions we can compute all class numbers for groups of order $n = pqr$ and then for each condition situation see which choice of factorisation turns out to be optimal. The resulting class numbers are shown in table 2.

As certain combinations of conditions and factorisations do not satisfy $(d, \phi(e)) = d$ there are a number of blank spaces. The entries in boldface are the smallest in their row. From this table it is evident that when n is a product of three primes the choice of d that gives the smallest class number is the largest d satisfying $(d, \phi(n/d)) = d$. It is easy to verify that this also holds when n has less than three prime factors. One might then conjecture this to be true for all squarefree n. Unfortunately this is not the case, and a smallest contradiction is obtained for $n = 930 = 2 \cdot 3 \cdot 5 \cdot 31$, a product of four primes. The smallest class number of a group of order 930 equals 24 and is obtained for $d = 10$. The largest d with $(d, \phi(n/d)) = d$ is in this case $d = 30$, but this choice of d produces larger class numbers than 24, the smallest one being 31. A complete analysis of the d-values which give the smallest class numbers when n is a product of four (or more) factors might make us able to conjecture a general rule for the optimal choice of d. However there are 64 cases to consider, so it is advisable to computerise the process. We leave this problem open for now.

5 Ideas for future work

As mentioned in the previous paragraph it would be nice to be able to find the optimal choice of d as a function of n as this would give a direct formula for the smallest class number among those of groups of a certain squarefree order.

Another view of the problem of finding small class numbers is to start out with a certain class number and then try to construct the largest group having this class number. (Or at least determine the order of this group.) As mentioned in the introduction general attempts in this direction exist. Confining ourselves to groups of squarefree order we can solve the problem as follows. We already have an algorithm to compute all class numbers a group of order n can have. By Theorem 3 we know that all groups with k conjugacy classes are of order at most k^3. Hence, computing the class numbers of all groups of orders up k^3 and checking which of them has class numbers exactly equal to k we obtain all groups with k conjugacy classes. We have performed such a computation for k up to 100 and the results are provided in tables 3 and 4.

It is likely that large group orders occurring in this table display certain properties of their prime factorisations, since this is what influences the **d**-sequence determining the class number. An idea for future work is to try to pinpoint those properties.

In the bigger picture this work on groups of squarefree order is one contribution to the greater challenge of understanding class numbers of groups in general. Obviously it would be interesting to try to generalise our results. The ultimate goal would be to see if a modified version can apply to groups in general, but perhaps more within reach if we can cover groups with presentations similar to (1).

Acknowledgments

I would like to express my gratitude to Professor John McKay for inviting me to Concordia University and for introducing me to the fascinating problem of class numbers of groups. Many thanks also to Olof Barr for valuable suggestions and comments during my work with this article.

Table 3: Squarefree group orders for which there exists a group with given class number.

$k(G)$	All squarefree $|G|$
1	1
2	2
3	3, 6
4	10
5	5, 14, 21
6	6
7	7, 22, 39, 42, 55
8	26, 78
9	30, 57, 114
10	10, 34, 42
11	11, 38, 110, 155, 186, 203
12	30, 42, 222
13	13, 46, 93, 205, 253, 258, 301, 310
14	14, 78, 110, 410
15	15, 30, 42, 111
16	58, 366, 406, 610
17	17, 62, 129, 210, 305, 402, 465, 497, 602, 689, 710, 737
18	66, 114, 330, 438
19	19, 70, 355, 474, 915, 979, 994, 1027
20	74, 210, 1010
21	21, 42, 66, 78, 165, 330, 546
22	22, 82, 310, 390, 406, 582, 1582
23	23, 86, 183, 506, 618, 791, 903, 1310, 1703, 1751, 1778
24	78, 546, 654, 930
25	70, 94, 105, 201, 505, 889, 1081, 1474, 1510, 2041, 2265, 2329
26	26, 186, 410, 506, 602, 1958
27	102, 219, 546, 570, 762, 1218, 1230, 2667, 2715
28	70, 106, 390, 798, 1378, 1810, 2758
29	29, 110, 237, 546, 834, 1910, 2054, 2189, 2954, 3165, 3197, 3629
30	30, 102, 114, 222, 1806
31	31, 118, 655, 798, 906, 930, 1711, 2110, 3346, 3406, 3615, 4063, 4351, 4378, 4431
32	122, 462, 770, 942, 1830, 4082
33	33, 66, 114, 273, 330, 465, 609, 930, 978, 1218, 1830, 4065
34	34, 130, 258, 610, 930, 994, 1378, 1474, 2410, 3934

Table 4: Largest squarefree group order for which there exists a group with given class number.

$k(G)$	Largest squarefree $\|G\|$	$k(G)$	Largest squarefree $\|G\|$
35	6371	68	46598
36	5430	69	46869
37	7282	70	46246
38	8138	71	53063
39	8130	72	26202
40	8734	73	57481
41	10121	74	59294
42	6510	75	26106
43	11563	76	63526
44	12630	77	67677
45	13101	78	31314
46	13906	79	72879
47	15279	80	74066
48	16230	81	78081
49	17185	82	76222
50	18030	83	84531
51	18930	84	48630
52	20842	85	91029
53	22085	86	92318
54	10218	87	73047
55	24586	88	100978
56	21206	89	104249
57	26502	90	84714
58	28918	91	111691
59	30299	92	115382
60	31794	93	117678
61	33661	94	121162
62	32402	95	126815
63	37086	96	95298
64	38134	97	135265
65	40721	98	139458
66	42378	99	143814
67	10402	100	146134

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Appendix

```
// Computation of all possible class numbers for given group order
//    n (n squarefree). The results are stored in Classtable. The
//    smallest class number for each n is stored in MinClasstable


Classtable:=[];
Lowerlimit:=2; Upperlimit:=100;
for n in [Lowerlimit..Upperlimit] do
  if IsSquarefree(n) then

    Classnrs:=[];

for d in Divisors(n) do
  if (GreatestCommonDivisor(d,EulerPhi(n div d))
  eq d) then
e:=n div d;

facte:=Factorisation(e);
m:=#facte;
MaxOrders:=[];
for i in [1..m] do
```

```
  MaxOrders:=Append(MaxOrders,GreatestCommonDivisor(d,facte[i][1]-1));
end for;
PossOrders:=[];
for i in [1..m] do
 PossOrders:=Append(PossOrders,Divisors(MaxOrders[i]));
end for;
  OrderSeqs:=[];
  for s in [1..#PossOrders[1]] do
  OrderSeqs:=Append(OrderSeqs,[PossOrders[1][s]]);
  end for;

  for j in [2..m] do
    NewOrderSeqs:=[];
    for k in [1..#PossOrders[j]] do
    for O in OrderSeqs do
      NewOrderSeqs:=Append(NewOrderSeqs,Append(O,PossOrders[j][k]));
    end for;
    end for;
    OrderSeqs:=NewOrderSeqs;
  end for;


alphaseqs:=[];

for k in [1..#OrderSeqs] do
alphaseq:=[];
for j in [1..d] do
  alpha:=1;
  for t in [1..#OrderSeqs[k]] do
    if ((j mod (OrderSeqs[k][t])) eq 0) then
      alpha:=alpha*facte[t][1];
    end if;
  end for;
  alphaseq:=Append(alphaseq,alpha);
end for;
alphaseqs:=Append(alphaseqs,alphaseq);
end for;

for alphaseq in alphaseqs do
  sum:=0;
  for j in Divisors(d) do
```

```
    insum:=1;
    for s in Divisors(d div j) do
      r:=#Factorisation(s);
      if not s eq 1 then
        insum:=insum+(-1)^r/s^2;
      end if;
    end for;
    insum:=insum*alphaseq[j]/j^2;


    sum:=sum+insum;
  end for;
  sum:=d*sum;
Classnrs:=Append(Classnrs,sum);
end for;
end if;
end for;

// Classnrs contains  all class numbers for
//groups of order n computed by our formula.

Classtable[n]:=SequenceToSet(Classnrs);
end if;
end for;
```