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REPRESENTATIONS OF FINITE GROUPS

**Autor:** Piveteau, Jean-Marc

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We can identify the irreducible faithful  $\mathbf{Q}[\mathbf{Z}/p]$ -Module  $\mathbf{Q}^{p-1}$  with  $\mathbf{Q}(\zeta_p)$  ( $\zeta_p$ : primitive  $p$ -th root of unity,  $1 \in \mathbf{Z}/p$  acts on  $\mathbf{Q}(\zeta_p)$  by multiplication with  $\zeta_p$ ). Any symmetric  $\sigma$ -invariant bilinear form is given by  $tr_{\mathbf{Q}(\zeta_p)/\mathbf{Q}}(axy)$  with  $a \in \mathbf{Q}(\zeta_p + \zeta_p^{-1})$  (cf. [4] or [6]). We write  $\gamma_a$  for the  $\sigma$ -invariant bilinear form corresponding to  $a \in \mathbf{Q}(\zeta_p + \zeta_p^{-1})$ .

(1.2) LEMMA. *The discriminant of  $\gamma_a$  in  $\mathbf{Q}/\mathbf{Q}^{*2}$  is equal to  $p \bmod \mathbf{Q}^{*2}$ .*

*Proof.* Since  $a \in \mathbf{L} := \mathbf{Q}(\zeta_p + \zeta_p^{-1})$  we have:  $\gamma_a = tr_{\mathbf{L}/\mathbf{Q}}(tr_{\mathbf{Q}(\zeta_p)/\mathbf{L}}axy)$ . An easy computation shows that  $tr_{\mathbf{Q}(\zeta_p)/\mathbf{L}}(axy)$  is a 2-dimensional symmetric  $\mathbf{L}$ -bilinearform with discriminant  $4 - (\zeta_p + \zeta_p^{-1})^2 \bmod \mathbf{L}^{*2} \in \mathbf{L}/\mathbf{L}^{*2}$ . Applying [7, Lemma 2.2] we conclude that the discriminant of  $\gamma_a$  is independant of  $a \in \mathbf{L}$ . Consider now the matrix representation of  $\sigma$  given before ( $\sigma$ : irreducible faithful  $\mathbf{Q}$ -representation of  $\mathbf{Z}/p$ ). Let  $C$  be the  $(p-1) \times (p-1)$ -matrix given by:

$$C := \begin{bmatrix} 2 & -1 & & & & \\ -1 & 2 & -1 & & & \\ & -1 & 2 & -1 & & \\ & & & \ddots & \ddots & \\ & & & & -1 & 2 \end{bmatrix}$$

It is easy to check that  $C$  is the matrix of a  $\sigma$ -invariant symmetric bilinear form. The Lemma follows since the determinant of  $C$  is equal to  $p$ .

## 2. ORTHOGONAL REPRESENTATIONS OF $p$ -GROUPS

Let  $p > 2$  be an odd prime. The integer  $l_{\mathbf{Q}}(p)$  is defined by

$$l_{\mathbf{Q}}(p) := \text{g.c.d. } \left\{ \begin{array}{l} m > 1 \\ \text{the } m\text{-fold direct sum } \sigma \oplus \dots \oplus \sigma \text{ of the irreducible faithful } \mathbf{Q}\text{-representation } \sigma \text{ of } \mathbf{Z}/p \text{ is equivalent to an orthogonal representation} \end{array} \right\}$$

The importance played by cyclic groups in the investigation of representations of  $p$ -groups is given by the following result (cf. [1, Theorem (1.10)]):

(2.1) PROPOSITION. *Let  $G$  be a finite  $p$ -group ( $p > 2$ ) and let  $\rho$  be an irreducible  $\mathbf{Q}$ -representation of  $G$ . Then either  $\rho$  is induced from a representation  $\theta$  of a normal subgroup of index  $p$ , or  $\rho$  factors through a  $\mathbf{Q}$ -representation of  $\mathbf{Z}/p$ .*

The degree of an irreducible non trivial  $\mathbf{Q}$ -representation of a finite  $p$ -group is therefore of the form  $p^k(p-1)$  ( $k=0, 1, 2, \dots$ ), cf. [1, Corollary (1.11)].

(2.2) PROPOSITION. *Let  $G$  be a  $p$ -group ( $p > 2$ ) and  $\rho: G \rightarrow SO_{2m}(\mathbf{Q})$  a representation of  $G$  with  $2m \neq 0 \bmod (l_{\mathbf{Q}}(p) \cdot (p-1))$ . Then  $\rho$  has a fixed point (i.e.  $\rho = 1 \oplus \tau$  where  $1$  is the unique 1-dimensional  $\mathbf{Q}$ -representation of  $G$ ).*

We will need the following lemma for the proof of (2.2):

(2.3) LEMMA. *Let  $\rho: G \rightarrow GL_m(\mathbf{Q})$  be an irreducible non trivial representation of the  $p$ -group  $G$  ( $p > 2$ ) and let  $\psi$  be a  $\rho$ -invariant symmetric bilinear form. If we write  $\sigma$  for the irreducible faithful representation of  $\mathbf{Z}/p$ , then there exist  $\sigma$ -invariant bilinear forms  $\Gamma_1, \dots, \Gamma_s$  such that  $\psi$  is equivalent to the orthogonal sum  $\Gamma_1 \perp \dots \perp \Gamma_s$ .*

*Proof.* Let  $p^k(p-1)$  be the degree of  $\rho$ . We prove the lemma by induction on  $k$ . For  $k = 0$ ,  $\rho$  factors through the irreducible faithful representation  $\sigma$  of  $\mathbf{Z}/p$ . Every  $\rho$ -invariant symmetric bilinear form  $\psi$  is therefore  $\sigma$ -invariant. For  $k > 0$ ,  $\rho$  is induced by a representation  $\theta$  of a normal subgroup  $H$  of index  $p$ . The restriction  $\rho_H$  of  $\rho$  to  $H$  splits in a direct sum:  $\rho = \theta_1 \oplus \dots \oplus \theta_p$  with  $\theta = \theta_1$  and  $\theta_i$  is irreducible for  $i = 1, \dots, p$ . By (1.1) we can assume that  $\mathbf{Q}^m$  is the orthogonal sum of the corresponding irreducible invariant subspaces. The assertion follows by induction.

*Proof of (2.2).* If  $G = \mathbf{Z}/p$ , we split  $\rho$  in a direct sum:  $\rho = n_0 1 \oplus n_1 \sigma$  ( $1$ : one dimensional representation of  $\mathbf{Z}/p$ ;  $\sigma$ : irreducible faithful representation of  $\mathbf{Z}/p$ ). If  $n_0 = 0$  then  $n_1$  must be a multiple of  $l_{\mathbf{Q}}(p)$ , i.e. we have  $2m = 0 \bmod (p-1)l_{\mathbf{Q}}(p)$ . Contradiction.

If  $G$  is not  $\mathbf{Z}/p$ , we split  $\rho$  in a direct sum of irreducible representations:  $\rho = \rho_1 \oplus \dots \oplus \rho_t$ , chosen in such a way that  $\mathbf{Q}^{2m}$  is the orthogonal sum of the corresponding invariant subspaces. Suppose now that  $\rho$  has no fixed points. Then all  $\rho_i$  are non trivial and it follows from (2.3) that any  $\rho$ -invariant symmetric bilinear form is equivalent to an orthogonal sum of  $\sigma$ -invariant symmetric bilinear forms. We can therefore construct a representation  $\mathbf{Z}/p \rightarrow SO_{2m}(\mathbf{Q})$  without fixed points, what contradicts the first part of the proof.

The rest of the section is devoted to the computation of  $l_{\mathbf{Q}}(p)$ ,  $p$  odd prime.

(2.4) PROPOSITION.  $l_{\mathbf{Q}}(p) = \begin{cases} 2 & \text{if } p \neq 7 \bmod 8 \\ 4 & \text{otherwise.} \end{cases}$

*Proof.* For each  $a \in \mathbf{Q}(\zeta_p + \zeta_p^{-1})$ , the discriminant of  $\gamma_a$  is not a square in  $\mathbf{Q}$  (cf. lemma (1.2)). Therefore  $l_{\mathbf{Q}}(p)$  must be even. The 4-fold orthogonal sum of a  $\mathbf{Q}$ -bilinear form is equivalent to the standard bilinear form, since every integer is sum of four squares. Let  $C$  be the matrix considered in the proof of lemma (1.2). If it is possible to find two rational numbers  $u$  and  $v$  such that the matrix  $X_{u,v}$

$$X_{u,v} := \begin{bmatrix} uC & 0 \\ 0 & vC \end{bmatrix}.$$

represents a bilinear form  $\xi_{u,v}$  which is equivalent to the standard one, then the representation  $\sigma \oplus \sigma$  is equivalent to an orthogonal representation. This sufficient condition is also necessary if  $p = 3 \pmod{4}$  (cf. [5]). For a prime  $p$ , let  $\mathbf{Q}_p$  be the field of  $p$ -adic numbers and write  $\mathbf{Q}_\infty$  for  $\mathbf{R}$  as usual. For  $a, b \in \mathbf{Q}$  and for  $v = 2, 3, 5, 7, \dots, \infty$  we write  $(a, b)_v$  for the Hilbert symbol of  $a$  and  $b$  relatively to  $\mathbf{Q}_v$ . For a bilinear form  $\alpha$  given in an orthogonal base by the diagonal matrix

$$\begin{bmatrix} a_1 & & & \\ & \ddots & & \\ & & \ddots & \\ & & & a_n \end{bmatrix}$$

we write  $H_v(\alpha)$  ( $v = 2, 3, \dots, \infty$ ) for the Hasse invariant, which is defined by

$$H_v(\alpha) = \prod_{i < j} (a_i, a_j)_v$$

Using the formulas given for example by [9] to compute the Hilbert symbol, one checks that:

$$\begin{aligned} H_v(\xi_{1,1}) &= 1 & \text{if } p \neq 3 \pmod{4} & \text{for } v = 2, 3, 5, 7, \dots, \infty, \\ H_2(\xi_{u,v}) &= -1 & \text{if } p = 7 \pmod{8} & \text{for any } u \text{ and any } v, \\ H_v(\xi_{2p,1}) &= 1 & \text{if } p = 1 \pmod{8} & \text{for } v = 2, 3, 5, 7, \dots, \infty. \end{aligned}$$

Since the discriminant of  $\xi_{u,v}$  is  $1 \in \mathbf{Q}/\mathbf{Q}^{*2}$  and since  $\xi_{u,v}$  is positive definite for any  $u$  and any  $v$ , it follows that  $\sigma \oplus \sigma$  is equivalent to an orthogonal representation if and only if  $p \neq 7 \pmod{8}$ . It remains to show that, for  $p = 7 \pmod{8}$ , the  $2n$ -fold orthogonal sum  $\mu$  given by the matrix  $H$ :

$$H := \begin{bmatrix} u_1 C \\ & \ddots \\ & & \ddots \\ & & & u_{2n} C \end{bmatrix}$$

is isomorphic to the standard bilinear form if and only if  $n$  is even. Let  $u_{\text{odd}}$  and  $u_{\text{even}}$  defined by:

$$u_{\text{even}} := \prod_{k=1}^n u_{2k} \quad u_{\text{odd}} := \prod_{k=1}^n u_{2k-1};$$

an easy computation shows that  $H_v(\xi_{u_{\text{even}}, u_{\text{odd}}}) = H_v(\mu)$  if  $n$  is odd. The proposition follows.

### 3. PROOF OF THE MAIN THEOREM

(3.1) LEMMA. *Let  $p$  be a prime number ( $p > 2$ ). For every integer  $m$  satisfying  $2m \neq 0 \pmod{(p-1) \cdot l_{\mathbf{Q}}(p)}$  we have  $F_{\mathbf{Q}}(m, p) = 1$ .*

*Proof.* Let  $G$  be a  $p$ -group,  $p > 2$ . It follows from (2.2) that any representation  $\rho$  of  $G$  splits:  $\rho = 1 \oplus \tau$  ( $1$  is the 1-dimensional representation of  $G$ ). Then we have  $e(\rho) = e(1)e(\tau) = 0$ .

We are now able to prove the main theorem. It has been showed in [3] that  $F_{\mathbf{Q}}(n) = 4$  if  $n$  is odd. If  $n$  is even, four cases have to be distinguished. If  $p = 2$  then the  $n/2^{N-2}$ -fold sum of the irreducible faithful representation of  $\mathbf{Z}/2^N$ , where  $2^N$  is the 2-primary part of  $\text{den}(B_n/n)$ , is an orthogonal representation with Euler class of order  $2^N$  (cf. [1]). Let now  $p$  be an odd prime. Since the irreducible faithful representation  $\nu$  of  $\mathbf{Z}/p^r$  ( $r \geq 1$ ) is induced by the irreducible faithful representation of  $\mathbf{Z}/p \subset \mathbf{Z}/p^r$ , the  $M$ -fold sum of  $\nu$  is equivalent to an orthogonal representation if and only if  $l_{\mathbf{Q}}(p)$  divides  $M$ . Write  $n = Np^k(p-1)$  with g.c.d.  $(N, p) = 1$ . If  $N$  is even, the  $2N$ -fold sum of the irreducible faithful representation of  $\mathbf{Z}/p^{k+1}$  is orthogonal and has Euler class of order  $p^{k+1}$  (cf. [1]); if  $N$  is odd and  $p \neq 7 \pmod{8}$  then the  $2N$ -fold sum of the irreducible faithful representation of  $\mathbf{Z}/p^{k+1}$  is orthogonal and has Euler class of order  $p^{k+1}$  (cf. [1]). In the three cases, the statement follows from the well known characterization of  $\text{den}(B_n/n)$  (cf. [1] for example). Eventually, applying (3.1) we see that  $F_{\mathbf{Q}}(n, p) = 1$  if  $N$  is odd and  $p = 7 \pmod{8}$ .