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Since

$$\frac{\partial I_i}{\partial x_k} + \sum_{l=1}^{r-s} V_{li} \frac{\partial I_{s+l}}{\partial x_k}$$

is homogeneous of degree $d_i - 1$, we conclude from Lemma 2.1 that

$$(2.2) \quad \frac{\partial I_i}{\partial x_k} + \sum_{l=1}^{r-s} V_{li} \frac{\partial I_{s+l}}{\partial x_k} = \sum_{j=1}^r B_j I_j, \quad 1 \leq i \leq s,$$

where the B_j 's are homogeneous and each term in (2.2) is homogeneous of degree $d_i - 1$. This forces $B_i = 0$. Multiply both sides of (2.2) by x_k and sum over k . We conclude, by Euler's identity for homogeneous polynomials,

$$(2.3) \quad d_i I_i + \sum_{l=1}^{r-s} V_{li} d_{s+l} I_{s+l} = \sum_{j=1}^r A_j I_j,$$

the A_j 's being homogeneous with $A_i = 0$.

(2.3) shows that $I_i \in (I_1, \dots, I_{i-1}, I_{i+1}, \dots, I_r)$, contradicting the minimality of the basis I_1, \dots, I_r . Hence I_1, \dots, I_r are algebraically independent and $r = n$.

2. THE THEOREM OF SHEPHARD AND TODD

We obtain in this section a converse to Chevalley's Theorem, thereby obtaining an invariant theoretical characterization of finite reflection groups. We first prove several preliminary results.

LEMMA 2.2. Let H be a finite group of linear transformations acting on the n -dimensional space V and fixing the $n - 1$ dimensional hyperplane π . The elements of H have a common eigenvector $v \in V - \pi$. Let $\sigma(v) = \zeta(\sigma)v$, $\sigma \in H$. $\zeta(\sigma)$ is an isomorphism from H into the multiplicative group of the roots of unity in k . It follows that H is a cyclic group.

REMARK. The above lemma is a consequence of Maschke's Theorem proven in section 2.3. We provide another proof below.

Proof. Let $\sigma_1 \in H$, $\sigma_1 \neq e$ (the identity of H). By the remark following Definition 2.1, there exists $v \in V - \pi$ such that $\sigma_1(v) = \zeta_1 v$, ζ_1 being a root of unity $\neq 1$. For $\sigma \in H$, let $\sigma(v) = \zeta(\sigma)v + p(\sigma)$, $\zeta(\sigma) \in k$ and $p(\sigma) \in \pi$. Let $\sigma^* = \sigma_1^{-1} \sigma^{-1} \sigma_1 \sigma$. Then $\sigma^*(v) = v + (1 - \zeta_1)p(\sigma)$. Since σ^* is of finite order, $(1 - \zeta_1)p(\sigma) = 0 \Rightarrow p(\sigma) = 0$. Hence $\sigma(v) = \zeta(\sigma)v$. $\zeta(\sigma)$ is clearly an isomorphism from H into U , the multiplicative group of

the roots of unity in k . U is known to be cyclic ([22], Vol. 1, p. 112). It follows that $\zeta(H)$, a subgroup of U , is cyclic and so H is cyclic.

THEOREM 2.2. *Let G be a finite group acting on the n -dimensional space V . Let I_1, \dots, I_n be homogeneous polynomials forming a basis for the invariants of G . Let d_1, \dots, d_n be the respective degrees of I_1, \dots, I_n . Then*

$$(2.4) \quad \prod_{i=1}^n d_i = |G|, \quad \sum_{i=1}^n (d_i - 1) = r$$

where $r =$ number of reflections in G .

Proof. By Theorem 1.2, I_1, \dots, I_n are algebraically independent. Let $I(x)$ be a homogeneous invariant of degree m . Then I is a linear combination of the monomials $I_1^{a_1} \dots I_n^{a_n}$ where $a_1 d_1 + \dots + a_n d_n = m$. Furthermore, these monomials are linearly independent over k , as I_1, \dots, I_n are algebraically independent over k . It follows that the dimension δ_m of homogeneous invariants of degree $m =$ number of non-negative integer solutions to $a_1 d_1 + \dots + a_n d_n = m$. Hence

$$(2.5) \quad \sum_{m=0}^{\infty} \delta_m t^m = \frac{1}{(1-t^{d_1}) \dots (1-t^{d_n})}.$$

(1.9) and (2.5) yield

$$(2.6) \quad \frac{1}{|G|} \sum_{\sigma \in G} \frac{1}{(1-\omega_1(\sigma)t) \dots (1-\omega_n(\sigma)t)} = \frac{1}{(1-t^{d_1}) \dots (1-t^{d_n})}$$

Expand both sides of (2.6) in powers of $(1-t)$. Let $\mathcal{R} =$ set of reflections in G and $\zeta(\sigma) =$ eigenvalue of the reflection σ which $\neq 1$. We have

$$(2.7) \quad \begin{aligned} & \frac{1}{|G|} \sum_{\sigma \in G} \frac{1}{(1-\omega_1(\sigma)t) \dots (1-\omega_n(\sigma)t)} \\ &= \frac{1}{|G|} \frac{1}{(1-t)^n} + \frac{1}{|G|} \sum_{\sigma \in \mathcal{R}} \frac{1}{1-\zeta(\sigma)} \frac{1}{(1-t)^{n-1}} + \dots \end{aligned}$$

$$(2.8) \quad \begin{aligned} \frac{1}{(1-t^{d_1}) \dots (1-t^{d_n})} &= \prod_{i=1}^n \frac{1}{d_i(1-t) - \binom{d_i}{2}(1-t)^2 + \dots \pm (1-t)^{d_i}} \\ &= \frac{1}{\prod_{i=1}^n d_i} \frac{1}{(1-t)^n} + \frac{1/2 \sum_{i=1}^n (d_i - 1)}{\prod_{i=1}^n d_i} \frac{1}{(1-t)^{n-1}} + \dots \end{aligned}$$

Equating coefficients of (2.7), (2.8), we get

$$(2.9) \quad \prod_{i=1}^n d_i = |G|, \quad \sum_{i=1}^n (d_i - 1) = 2 \sum_{\sigma \in \mathcal{R}} \frac{1}{1 - \zeta(\sigma)}.$$

We evaluate the sum

$$\sum_{\sigma \in \mathcal{R}} \frac{1}{1 - \zeta(\sigma)} :$$

Let π be any r.h. Let $H_\pi = \{\sigma \mid \sigma \in G \text{ and } \sigma \text{ fixes } \pi\}$. Thus H_π is the subgroup of G consisting of the identity and those reflections in G with r.h. π . Applying Lemma 2.2 to H_π , we conclude that there exists $v \notin \pi$ such that $\sigma(v) = \zeta(\sigma)v$ for $\sigma \in H_\pi$. Let $H'_\pi = H_\pi - \{e\}$. Since $\zeta(\sigma^{-1}) = (\zeta(\sigma))^{-1}$, we obtain

$$(2.10) \quad \begin{aligned} \sum_{\sigma \in H'_\pi} \frac{1}{1 - \zeta(\sigma)} &= \sum_{\sigma \in H'_\pi} \frac{1}{1 - \zeta(\sigma^{-1})} \\ &= \sum_{\sigma \in H'_\pi} \left(1 - \frac{1}{1 - \zeta(\sigma)}\right) = |H'_\pi| - \sum_{\sigma \in H'_\pi} \frac{1}{1 - \zeta(\sigma)}. \end{aligned}$$

Hence

$$(2.11) \quad \sum_{\sigma \in H'_\pi} \frac{1}{1 - \zeta(\sigma)} = \frac{|H'_\pi|}{2}.$$

Summing both sides of (2.11) over all r.h. π , we get

$$(2.12) \quad \sum_{\sigma \in \mathcal{R}} \frac{1}{1 - \zeta(\sigma)} = \frac{r}{2}.$$

(2.9), (2.12) yield Theorem 2.2.

THEOREM 2.3. *Let f_1, \dots, f_n be polynomials in the variables x_1, \dots, x_n . f_1, \dots, f_n are algebraically independent over $k \Leftrightarrow$*

$$\frac{\partial(f_1, \dots, f_n)}{\partial(x_1, \dots, x_n)} \neq 0.$$

Proof. Suppose that f_1, \dots, f_n are algebraically independent. Then $G(f_1, \dots, f_n) = 0$ for some polynomial $G = G(y_1, \dots, y_n)$. Assume that $G(y_1, \dots, y_n)$ is of minimal positive degree. Differentiating this relation with respect to x_j , we get

$$(2.13) \quad \sum_{i=1}^n \frac{\partial G}{\partial y_i} (f_1, \dots, f_n) \frac{\partial f_i}{\partial x_j} = 0, \quad 1 \leq j \leq n.$$

(2.13) is a system of linear equations (with coefficients in $k(x_1, \dots, x_n)$) in the unknowns $H_i(x) = \frac{\partial G}{\partial y_i} (f_1, \dots, f_n)$, $1 \leq i \leq n$. $\frac{\partial G}{\partial y_i} \neq 0$ for some i ,

as G is not constant, and $\deg \frac{\partial G}{\partial y_i} < \deg G$. It follows that the corresponding

$H_i(x) \neq 0$. Thus the linear system (2.13) has a non-zero solution, so that its determinant

$$\frac{\partial (f_1, \dots, f_n)}{\partial (x_1, \dots, x_n)} \neq 0.$$

Conversely, let f_1, \dots, f_n be algebraically independent. For each i , x_i, f_1, \dots, f_n are algebraically dependent. Hence there exists a polynomial $G_i(x_i, y_1, \dots, y_n)$ of minimal positive degree in x_i such that $G_i(x_i, f_1, \dots, f_n) = 0$. Differentiating these relations with respect to x_k , we get

$$(2.14) \quad \sum_{j=1}^n \frac{\partial G_i}{\partial y_j} (x_i, f_1, \dots, f_n) \frac{\partial f_j}{\partial x_k} + \frac{\partial G_i}{\partial x_k} (x_i, f_1, \dots, f_n) \delta_{ik}, \quad 1 \leq k \leq n,$$

δ_{ik} denoting the Kronecker symbol. (2.14) may be rewritten in matrix notation as

$$(2.15) \quad \begin{pmatrix} \frac{\partial G_i}{\partial y_j} \end{pmatrix} \cdot \begin{pmatrix} \frac{\partial f_i}{\partial x_j} \end{pmatrix} = D$$

where the entries of D are

$$- \delta_{ij} \frac{\partial G_i}{\partial x_j}.$$

$\det D \neq 0$, as $x_i - \text{degree of } \frac{\partial G_i}{\partial x_i} < x_i - \text{degree of } G_i$, $1 \leq i \leq n$.

It follows from (2.15) that $\frac{\partial (f_1, \dots, f_n)}{\partial (x_1, \dots, x_n)} \neq 0$.

THEOREM 2.4. (Shephard and Todd [19]). *Let G be a finite group acting on the n -dimensional space V . Suppose there exists a basis of n homogeneous polynomials for the invariants of G . Then G is a finite reflection group.*

Proof. Let H be the subgroup of G generated by the reflections in G . By assumption G has n basic homogeneous invariants which, by Theorem 1.2, are algebraically independent. Since H is a finite reflection group, we conclude from Chevalley's Theorem that H has n basic homogeneous invariants J_1, \dots, J_n which are algebraically independent. Each I_i is invariant under H so that $I_i = I_i(J_1, \dots, J_n)$, the latter quantity denoting a polynomial in the J_i 's. We may assume that $I_i(J_1, \dots, J_n)$ is a linear combination of monomials $J_1^{a_1} \dots J_n^{a_n}$ whose x -degree = $\deg I_i$. We have

$$(2.16) \quad \frac{\partial (I_1, \dots, I_n)}{\partial (x_1, \dots, x_n)} = \frac{\partial (I_1, \dots, I_n)}{\partial (J_1, \dots, J_n)} \cdot \frac{\partial (J_1, \dots, J_n)}{\partial (x_1, \dots, x_n)}$$

By Theorem 2.3,

$$\frac{\partial (I_1, \dots, I_n)}{\partial (x_1, \dots, x_n)} \neq 0$$

and (2.16) then shows that

$$\frac{\partial (I_1, \dots, I_n)}{\partial (J_1, \dots, J_n)} \neq 0.$$

It follows that there is a rearrangement k_1, \dots, k_n of $1, \dots, n$ so that

$$\frac{\partial I_{k_1}}{\partial J_1} \dots \frac{\partial I_{k_n}}{\partial J_n} \neq 0.$$

Hence $I_{k_i}(J_1, \dots, J_n)$ is of positive degree in J_i and $\deg I_{k_i} \geq \deg J_i$, $1 \leq i \leq n$. Applying Theorem 2.2 both to G and H , we obtain

$$(2.17) \quad \prod_{i=1}^n \deg J_i = |H|, \quad \prod_{i=1}^n \deg I_i = |G|$$

$$(2.18) \quad \sum_{i=1}^n (\deg J_i - 1) = \sum_{i=1}^n (\deg I_i - 1) = r$$

where r = number of reflections in G = number of reflections in H .

Since $\deg I_{k_i} \geq \deg J_i$, $1 \leq i \leq n$, we conclude from (2.18) that $\deg I_{k_i} = \deg J_i$, $1 \leq i \leq n$. Hence $\prod_{i=1}^n \deg I_i = \prod_{i=1}^n \deg J_i$, and we conclude from (2.17) that $|G| = |H|$. Thus $G = H$ and G is a finite reflection group.