PART II REPRESENTATION THEORY
SHEET 3

Unless otherwise stated, all groups here are finite, and all vector spaces are finite-dimensional over a field F of characteristic zero, usually $\mathbb{C}$.

1 Recall the character table of S_4 from Sheet 2. Find all the characters of S_5 induced from the irreducible characters of S_4. Hence find the complete character table of S_5.

Repeat, replacing S_4 by the subgroup $\langle (12345), (2354) \rangle$ of order 20 in S_5.

2 Recall the construction of the character table of the dihedral group D_{10} of order 10 from Sheet 2.

(a) Use induction from the subgroup D_{10} of A_5 to A_5 to obtain the character table of A_5.

(b) Let G be the subgroup of $\mathrm{SL}_2(\mathbb{F}_5)$ consisting of upper triangular matrices. Compute the character table of G. Hint: bear in mind that there is an isomorphism $G/Z \to D_{10}$)

3 Let H be a subgroup of the group G. Show that for every irreducible representation ρ for G there is an irreducible representation ρ' for H with ρ a component of the induced representation $\mathrm{Ind}_H^G \, \rho'$.

Prove that if A is an abelian subgroup of G then every irreducible representation of G has dimension at most $|G : A|$.

4 Obtain the character table of the dihedral group D_{2m} of order $2m$, by using induction from the cyclic subgroup C_m. Note that it matters whether m is odd or even.

5 Calculate $\chi_{\Lambda^2 \rho}$ and $\chi_{S^2 \rho}$, where ρ is the irreducible representation of dimension 2 of D_8; repeat this for Q_8. Which of these characters contains the trivial character in the two cases?

6 Let $\rho : G \to \mathrm{GL}(V)$ be a representation of G of dimension d.

(a) Compute the dimension of $S^n V$ and $\Lambda^n V$ for all n.

(b) Let $g \in G$ and let $\lambda_1, \ldots, \lambda_d$ be the eigenvalues of g on V. What are the eigenvalues of g on $S^n V$ and $\Lambda^n V$?

(c) Let $f(x) = \det(g - xI)$ be the characteristic polynomial of g on V. Describe how to obtain the trace $\chi_{\Lambda^n V}(g)$ from the coefficients of $f(x)$.

(d)* Find a relation between $\chi_{S^n V}(g)$ and the polynomial $f(x)$. [Hint: do the case where V has dimension 1 first.]

7 Let G be the symmetric group S_n acting naturally on the set $X = \{1, \ldots, n\}$. For any integer $r \leqslant \frac{n}{2}$, write X_r for the set of all r-element subsets of X, and let π_r be the permutation character of the action of G on X_r. Observe $\pi_r(1) = |X_r| = \binom{n}{r}$. If $0 \leqslant \ell \leqslant k \leqslant n/2$, show that

$$\langle \pi_k, \pi_\ell \rangle = \ell + 1.$$

Let $m = n/2$ if n is even, and $m = (n-1)/2$ if n is odd. Deduce that S_n has distinct irreducible characters $\chi^{(n)} = 1_G, \chi^{(n-1,1)}, \chi^{(n-2,2)}, \ldots, \chi^{(n-m,m)}$ such that for all $r \leqslant m$,

$$\pi_r = \chi^{(n)} + \chi^{(n-1,1)} + \chi^{(n-2,2)} + \cdots + \chi^{(n-r,r)}.$$

In particular the class functions $\pi_r - \pi_{r-1}$ are irreducible characters of S_n for $1 \leqslant r \leqslant n/2$ and equal to $\chi^{(n-r,r)}$.

8 Given any complex representation V of the cyclic group $\mathbf{Z}/2$, write down the projections to the two isotypical summands of V, directly from the action of G on V. Show that your formulae give a decomposition of V as a direct sum of two subspaces even if V is an infinite-dimensional representation of $\mathbf{Z}/2$.

More generally, given any complex representation V of any finite cyclic group $\mathbf{Z}/n$, write down the projections to the n isotypical summands of V, directly from the action of G on V.

9 If $\rho : G \to \mathrm{GL}(V)$ is an irreducible complex representation for G affording character χ, find the characters of the representation spaces $V \otimes V$, $\mathrm{Sym}^2(V)$ and $\Lambda^2(V)$.

Define the *Frobenius-Schur indicator* $\iota\chi$ of χ by

$$\iota\chi = \frac{1}{|G|}\sum_{x\in G}\chi(x^2)$$

and show that

$$\iota\chi = \begin{cases} 0, & \text{if } \chi \text{ is not real-valued} \\ \pm 1, & \text{if } \chi \text{ is real-valued.} \end{cases}$$

[Remark. The sign $+$, resp. $-$, indicates whether $\rho(G)$ preserves an orthogonal, respectively, symplectic form on V, and whether or not the representation can be realised over the reals. You can read about it in Isaacs or in James and Liebeck.]

10 The group $G\times G$ acts on G by $(g,h)(x) = gxh^{-1}$. In this way, the regular representation space $\mathbb{C}G$ becomes a $G\times G$-space. (So far, we only considered $\mathbb{C}G$ as a representation space of the group $G \times \{1\} \leq G \times G$.)

Determine the character π of $G\times G$ in this action. For each irreducible character $\chi\psi$ of $G\times G$, determine its multiplicity in π. Compare π to the character of the subgroup $G\times\{1\}$ in this action.

11 If θ is a faithful character of the group G, which takes r distinct values on G, prove that each irreducible character of G is a constituent of θ to power i for some $i < r$.
[Hint: assume that $\langle \chi, \theta^i\rangle = 0$ for all $i < r$; use the fact that the Vandermonde $r \times r$ matrix involving the row of the distinct values $a_1, ..., a_r$ of θ is nonsingular to obtain a contradiction.]

12 Construct the character table of the symmetric group S_6. Identify which of your characters are equal to the characters $\chi^{(6)}, \chi^{(5,1)}, \chi^{(4,2)}, \chi^{(3,3)}$ constructed in question 7.

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Comments and corrections on this sheet may be emailed to `sm@dpmms.cam.ac.uk`