Exercise 8.2 (*Exercise 11, Sheet 3*)

Find a $\mathbb{C}$-basis of $\mathcal{C}l(G)$ and deduce that $\dim_{\mathbb{C}} \mathcal{C}l(G) = |C(G)|$.

Proposition 8.3

The binary operation

$$\begin{array}{rccl} \langle\, ,\, \rangle_G : & \mathcal{F}(G,\mathbb{C}) \times \mathcal{F}(G,\mathbb{C}) & \longrightarrow & \mathbb{C} \\ & (f_1, f_2) & \mapsto & \langle f_1, f_2 \rangle_G := \frac{1}{|G|} \sum_{g \in G} f_1(g)\overline{f_2(g)} \end{array}$$

is a scalar product on $\mathcal{F}(G,\mathbb{C})$.

Proof: It is straightforward to check that $\langle\, ,\, \rangle_G$ is sesquilinear and Hermitian (Exercise 11, Sheet 3); it is positive definite because for every $f \in \mathcal{F}(G,\mathbb{C})$,

$$\langle f, f \rangle = \frac{1}{|G|} \sum_{g \in G} f(g)\overline{f(g)} = \frac{1}{|G|} \sum_{g \in G} \underbrace{|f(g)|^2}_{\in \mathbb{R}_{\geqslant 0}} \geqslant 0$$

and moreover $\langle f, f \rangle = 0$ if and only if $f = 0$. ■

Remark 8.4

Obviously, the scalar product $\langle\, ,\, \rangle_G$ restricts to a scalar product on $\mathcal{C}l(G)$. Moreover, if f_2 is a character of G, then by Property 7.4(d) we can write

$$\langle f_1, f_2 \rangle_G = \frac{1}{|G|} \sum_{g \in G} f_1(g)\overline{f_2(g)} = \frac{1}{|G|} \sum_{g \in G} f_1(g) f_2(g^{-1}) .$$

The next theorem is the third key result of this lecture. It tells us that the irreducible characters of a finite group form an orthonormal system in $\mathcal{C}l(G)$ with respect to the scalar product $\langle\, ,\, \rangle_G$.

Theorem 8.5 (*1st Orthogonality Relations*)

If $\rho_V : G \longrightarrow \mathrm{GL}(V)$ and $\rho_W : G \longrightarrow \mathrm{GL}(W)$ are two irreducible $\mathbb{C}$-representations with characters χ_V and χ_W respectively, then

$$\langle \chi_V, \chi_W \rangle_G = \frac{1}{|G|} \sum_{g \in G} \chi_V(g)\chi_W(g^{-1}) = \begin{cases} 1 & \text{if } \rho_V \sim \rho_W, \\ 0 & \text{if } \rho_V \not\sim \rho_W. \end{cases}$$

Proof: Choose ordered $\mathbb{C}$-bases $E := (e_1, \ldots, e_n)$ and $F := (f_1, \ldots, f_m)$ of V and W respectively. Then for each $g \in G$ write $Q(g) := \big(\rho_V(g)\big)_E$ and $P(g) := \big(\rho_W(g)\big)_F$.
If $\rho_V \not\sim \rho_W$ compute

$$\begin{aligned} \langle \chi_V, \chi_W \rangle_G = \frac{1}{|G|} \sum_{g \in G} \chi_V(g)\chi_W(g^{-1}) &= \frac{1}{|G|} \sum_{g \in G} \mathrm{Tr}\,\big(Q(g)\big)\, \mathrm{Tr}\,\big(P(g^{-1})\big) \\ &= \frac{1}{|G|} \sum_{g \in G} \Big(\sum_{i=1}^{n} Q(g)_{ii}\Big)\Big(\sum_{j=1}^{m} P(g^{-1})_{jj}\Big) \\ &= \sum_{i=1}^{n}\sum_{j=1}^{m} \underbrace{\frac{1}{|G|} \sum_{g \in G} Q(g)_{ii} P(g^{-1})_{jj}}_{=0 \text{ by (a) of Schur's Relations}} = 0 \end{aligned}$$

and similarly if $W = V$, then $P = Q$ and

$$\langle \chi_V, \chi_V \rangle_G = \sum_{i=1}^{n} \sum_{j=1}^{m} \underbrace{\frac{1}{|G|} \sum_{g \in G} Q(g)_{ii} Q(g^{-1})_{jj}}_{=\frac{1}{n}\delta_{ij}\delta_{ij} \text{ by (b) of Schur's Relations}} = \sum_{i=1}^{n} \frac{1}{n} = 1\,.$$

■

9 Consequences of the 1st Orthogonality Relations

In this section we use the 1st Orthogonality Relations in order to deduce a series of fundamental properties of the (irreducible) characters of finite groups.

Corollary 9.1 (*Linear independence*)

The irreducible characters of G are $\mathbb{C}$-linearly independent.

Proof: Assume $\sum_{i=1}^{s} \lambda_i \chi_i = 0$, where $\chi_1, \ldots, \chi_s$ are pairwise distinct irreducible characters of G, $\lambda_1, \ldots, \lambda_s \in \mathbb{C}$ and $s \in \mathbb{Z}_{>0}$. Then the 1st Orthogonality Relations yield

$$0 = \langle \sum_{i=1}^{s} \lambda_i \chi_i, \chi_j \rangle_G = \sum_{i=1}^{s} \lambda_i \underbrace{\langle \chi_i, \chi_j \rangle_G}_{=\delta_{ij}} = \lambda_j$$

for each $1 \leqslant j \leqslant s$. The claim follows. ■

Corollary 9.2 (*Finiteness*)

There are at most $|C(G)|$ irreducible characters of G. In particular, there are only a finite number of them.

Proof: By Corollary 9.1 the irreducible characters of G are $\mathbb{C}$-linearly independent. By Lemma 7.7 irrreducible characters are elements of the $\mathbb{C}$-vector space $\mathcal{C}l(G)$. Therefore there exists at most $\dim_{\mathbb{C}} \mathcal{C}l(G) = |C(G)| < \infty$ of them. ■

Corollary 9.3 (*Multiplicities*)

Let $\rho_V : G \longrightarrow \mathrm{GL}(V)$ be a $\mathbb{C}$-representation and let $\rho_V = \rho_{V_1} \oplus \cdots \oplus \rho_{V_s}$ be a decomposition of ρ_V into irreducible subrepresentations. Then the following assertions hold.

(a) If $\rho_W : G \longrightarrow \mathrm{GL}(W)$ is an irreducible $\mathbb{C}$-representation of G, then the multiplicity of ρ_W in $\rho_{V_1} \oplus \cdots \oplus \rho_{V_s}$ is equal to $\langle \chi_V, \chi_W \rangle_G$.

(b) This multiplicity is independent of the choice of the chosen decomposition of ρ_V into irreducible subrepresentations.

Proof: (a) We may assume that we have chosen the labelling such that

$$\rho_V = \rho_{V_1} \oplus \cdots \oplus \rho_{V_l} \oplus \rho_{V_{l+1}} \oplus \cdots \oplus \rho_{V_s}\,,$$

where $\rho_{V_i} \sim \rho_W \ \forall\ 1 \leqslant i \leqslant l$ and $\rho_{V_j} \not\sim \rho_W \ \forall\ l+1 \leqslant j \leqslant s$. Thus $\chi_{V_i} = \chi_W \ \forall\ 1 \leqslant i \leqslant l$ by Lemma 7.3. Therefore the 1st Orthogonality Relations yield

$$\langle \chi_V, \chi_W \rangle_G = \sum_{i=1}^{l} \langle \chi_{V_i}, \chi_W \rangle_G + \sum_{j=l+1}^{s} \langle \chi_{V_j}, \chi_W \rangle_G = \sum_{i=1}^{l} \underbrace{\langle \chi_W, \chi_W \rangle_G}_{=1} + \sum_{j=l+1}^{s} \underbrace{\langle \chi_{V_j}, \chi_W \rangle_G}_{=0} = l\,.$$

(b) Obvious, since $\langle \chi_V, \chi_W \rangle_G$ depends only on V and W, but not on the chosen decomposition. ■

We can now prove that the converse of Lemma 7.3 holds.

Corollary 9.4 (*Equality of characters*)

Let $\rho_V : G \longrightarrow \mathrm{GL}(V)$ and $\rho_W : G \longrightarrow \mathrm{GL}(W)$ be $\mathbb{C}$-representations with characters χ_V and χ_W respectively. Then:

$$\chi_V = \chi_W \quad \Leftrightarrow \quad \rho_V \sim \rho_W\,.$$

Proof: "$\Leftarrow$": The sufficient condition is the statement of Lemma 7.3.

"$\Rightarrow$": To prove the necessary condition decompose ρ_V and ρ_W into direct sums of irreducible subrepresentations

$$\rho_V = \underbrace{\rho_{V_{1,1}} \oplus \cdots \oplus \rho_{V_{1,m_1}}}_{\text{all } \sim \rho_{V_1}} \oplus \cdots \oplus \underbrace{\rho_{V_{s,1}} \oplus \cdots \oplus \rho_{V_{s,m_s}}}_{\text{all } \sim \rho_{V_s}}\,,$$
$$\rho_W = \underbrace{\rho_{W_{1,1}} \oplus \cdots \oplus \rho_{W_{1,p_1}}}_{\text{all } \sim \rho_{V_1}} \oplus \cdots \oplus \underbrace{\rho_{W_{s,1}} \oplus \cdots \oplus \rho_{W_{s,p_s}}}_{\text{all } \sim \rho_{V_s}}\,,$$

where $m_i, p_i \geqslant 0$ for all $1 \leqslant i \leqslant s$ and the ρ_{V_i}'s are pairwise non-equivalent irreducible $\mathbb{C}$-representations of G. (Some of the m_i, p_i's may be zero!) Now, as we assume that $\chi_V = \chi_W$, for each $1 \leqslant i \leqslant s$ Corollary 9.3 yields

$$m_i = \langle \chi_V, \chi_{V_i} \rangle_G = \langle \chi_W, \chi_{V_i} \rangle_G = p_i\,,$$

hence $\rho_V \sim \rho_W$. ■

Corollary 9.5 (*Irreducibility criterion*)

A $\mathbb{C}$-representation $\rho_V : G \longrightarrow \mathrm{GL}(V)$ is irreducible if and only if $\langle \chi_V, \chi_V \rangle_G = 1$.

Proof: "$\Rightarrow$": holds by the 1st Orthogonality Relations.

"$\Leftarrow$": As in the previous proof, write

$$\rho_V = \underbrace{\rho_{V_{1,1}} \oplus \cdots \oplus \rho_{V_{1,m_1}}}_{\text{all } \sim \rho_{V_1}} \oplus \cdots \oplus \underbrace{\rho_{V_{s,1}} \oplus \cdots \oplus \rho_{V_{s,m_s}}}_{\text{all } \sim \rho_{V_s}}\,,$$

where $m_i \geqslant 1$ for all $1 \leqslant i \leqslant s$ and the ρ_{V_i}'s are pairwise non-equivalent irreducible $\mathbb{C}$-representations of G. Then, using the assumption, the sesquilinearity of the scalar product and the 1st Orthogonality Relations, we obtain that

$$1 = \langle \chi_V, \chi_V \rangle_G = \sum_{i=1}^{s} m_i^2 \underbrace{\langle \chi_{V_i}, \chi_{V_i} \rangle_G}_{=1} = \sum_{i=1}^{s} m_i^2\,.$$

Hence, w.l.o.g. we may assume that $m_1 = 1$ and $m_i = 0 \ \forall\ 2 \leqslant i \leqslant s$, so that $\rho_V = \rho_{V_1}$ is irreducible. ■

Theorem 9.6

The set $\mathrm{Irr}(G)$ is an orthonormal $\mathbb{C}$-basis (w.r.t. $\langle\, ,\, \rangle_G$) of the $\mathbb{C}$-vector space $\mathcal{C}l(G)$ of class functions on G.

Proof: We already know that $\mathrm{Irr}(G)$ is a $\mathbb{C}$-linearly independent set and also that it forms an orthonormal system of $\mathcal{C}l(G)$ w.r.t. $\langle\, ,\, \rangle_G$. Hence it remains to prove that $\mathrm{Irr}(G)$ generates $\mathcal{C}l(G)$. So let $X := \langle \mathrm{Irr}(G)\rangle_{\mathbb{C}}$ be the $\mathbb{C}$-subspace of $\mathcal{C}l(G)$ generated by $\mathrm{Irr}(G)$. It follows that

$$\mathcal{C}l(G) = X \oplus X^{\perp}$$

where $X^{\perp}$ denotes the orthogonal of X with respect to the scalar product $\langle\, ,\, \rangle_G$ (see GDM). Thus it is enough to prove that $X^{\perp} = 0$. So let $f \in X^{\perp}$, set $\check{f} := \sum_{g\in G} \overline{f(g)}g \in \mathbb{C}G$ and we prove the following assertions:

(1) $\check{f} \in Z(\mathbb{C}G)$ (the centre of $\mathbb{C}G$): let $h \in G$ and compute

$$h\check{f}h^{-1} = \sum_{g\in G} \overline{f(g)}hg\cdot h^{-1} \overset{s:=hgh^{-1}}{=} \sum_{s\in G} \underbrace{\overline{f(h^{-1}sh)}}_{=f(s)}s = \sum_{s\in G} \overline{f(s)}s = \check{f}\,.$$

Hence $h\check{f} = \check{f}h$ and this equality extends by $\mathbb{C}$-linearity to the whole of $\mathbb{C}G$, so that $\check{f} \in Z(\mathbb{C}G)$.

(2) If V is a simple $\mathbb{C}G$-module with character χ_V, then the external multiplication by $\check{f}$ on V is scalar multiplication by $\frac{|G|}{\dim_{\mathbb{C}} V}\langle \chi_V, f\rangle_G \in \mathbb{C}$: first notice that the external multiplication by $\check{f}$ on V, i.e. the map

$$\check{f}\cdot - : V \longrightarrow V, v \mapsto \check{f}\cdot v$$

is $\mathbb{C}G$-linear. Indeed, for each $x \in \mathbb{C}G$ and each $v \in V$ we have

$$\check{f}\cdot(x\cdot v) = (\check{f}x)\cdot v = (x\check{f})\cdot v = x\cdot(\check{f}\cdot v)$$

because $\check{f} \in Z(\mathbb{C}G)$. Therefore, by Schur's Lemma, there exists a scalar $\lambda \in \mathbb{C}$ such that $\check{f}\cdot - = \lambda\,\mathrm{Id}_V$. Moreover,

$$\lambda = \frac{1}{n}\mathrm{Tr}(\lambda\,\mathrm{Id}_V) = \frac{1}{n}\mathrm{Tr}(\check{f}\cdot -) = \frac{1}{n}\sum_{g\in G}\overline{f(g)}\underbrace{\mathrm{Tr}\left(\text{mult. by } g \text{ on } V\right)}_{=\chi_V(g)} = \frac{1}{n}\sum_{g\in G}\overline{f(g)}\chi_V(g) = \frac{|G|}{n}\langle \chi_V, f\rangle_G\,.$$

(3) If V is a simple $\mathbb{C}G$-module with character χ_V, then the external multiplication by $\check{f}$ on V is zero: indeed, $\langle \chi_V, f\rangle_G = 0$ because $f \in X^{\perp}$ and the claim follows from (2).

(4) $f = 0$: indeed, as the external multiplication by $\check{f}$ is zero on every simple $\mathbb{C}G$-module, it is zero on every $\mathbb{C}G$-module, because any $\mathbb{C}G$-module can be decomposed as the direct sum of simple submodules by the Corollary to Maschke's Theorem. In particular, the external multiplication by $\check{f}$ is zero on $\mathbb{C}G$. Hence

$$0 = \check{f}\cdot 1_{\mathbb{C}G} = \check{f} = \sum_{g\in G}\overline{f(g)}g$$

and we obtain that $\overline{f(g)} = 0$ for each $g \in G$ because G is a $\mathbb{C}$-basis of $\mathbb{C}G$. But then $f(g) = 0$ for each $g \in G$ and it follows that $f = 0$. ■

Corollary 9.7

The number of pairwise non-equivalent irreducible characters of G is equal to the number of conjugacy classes of G. In other words,

$$|\operatorname{Irr}(G)| = |C(G)|.$$

Proof: By Theorem 9.6 the set $\operatorname{Irr}(G)$ is a $\mathbb{C}$-basis of the space $\mathcal{C}l(G)$ of class functions on G. Hence

$$|\operatorname{Irr}(G)| = \dim_{\mathbb{C}} \mathcal{C}l(G) = |C(G)|$$

where the second equality holds by Exercise 8.2. ■

Corollary 9.8

Let $f \in \mathcal{C}l(G)$. Then the following assertions hold:

(a) $f = \sum_{\chi \in \operatorname{Irr}(G)} \langle f, \chi \rangle_G \, \chi$;

(b) $\langle f, f \rangle_G = \sum_{\chi \in \operatorname{Irr}(G)} \langle f, \chi \rangle_G^2$;

(c) f is a character $\iff \langle f, \chi \rangle_G \in \mathbb{Z}_{\geqslant 0} \;\; \forall\, \chi \in \operatorname{Irr}(G)$; and

(d) $f \in \operatorname{Irr}(G) \iff f$ is a character and $\langle f, f \rangle_G = 1$.

Proof: (a)+(b) hold for any orthonormal basis with respect to a given scalar product (GDM).

(c) '$\Rightarrow$': If f is a character, then by Corollary 9.3 the complex number $\langle f, \chi_i \rangle_G$ is the multiplicity of χ_i as a constituent of f, hence a non-negative integer.

'$\Leftarrow$': If for each $\chi \in \operatorname{Irr}(G)$, $\langle f, \chi \rangle_G =: m_\chi \in \mathbb{Z}_{\geqslant 0}$, then f is the character of the representation

$$\rho := \bigoplus_{\chi \in \operatorname{Irr}(G)} \bigoplus_{j=1}^{m_\chi} \rho(\chi)$$

where $\rho(\chi)$ is a $\mathbb{C}$-representation affording the character χ.

(d) The necessary condition is given by the 1st Orthogonality Relations. The sufficient condition follows from (b) and (c). ■

Exercise 9.9 (*Exercise 12, Sheet 3*)

Let V be a $\mathbb{C}G$-module (finite dimensional) with character χ_V. Consider the $\mathbb{C}$-subspace $V^G := \{v \in V \mid g \cdot v = v \; \forall\, g \in G\}$. Prove that

$$\dim_{\mathbb{C}} V^G = \frac{1}{|G|} \sum_{g \in G} \chi_V(g)$$

1. considering the scalar product of χ_V with the trivial character $\mathbf{1}_G$;
2. seeing V^G as the image of the projector $\pi : V \twoheadrightarrow V, v \mapsto \frac{1}{|G|} \sum_{g \in G} g \cdot v$.

10 The Regular Character

Recall from Example 1(d) that a finite G-set X induces a *permutation representation*

$$\begin{array}{rccl}\rho_X: & G & \longrightarrow & \mathrm{GL}(V) \\ & g & \mapsto & \rho_X(g) : V \longrightarrow V, e_x \mapsto e_{g\cdot x}\end{array}$$

where V is a $\mathbb{C}$-vector space with basis $\{e_x \mid x \in X\}$ (i.e. indexed by the set X). Given $g \in G$ write $\mathrm{Fix}_X(g) := \{x \in X \mid g \cdot x = x\}$ for the set of fixed points of g on X.

Proposition 10.1 (*Character of a permutation representation*)

Let X be a G-set and let χ_X denote the character of the associated permutation representation ρ_X. Then

$$\chi_X(g) = |\,\mathrm{Fix}_X(g)| \qquad \forall\, g \in G\,.$$

Proof: Let $g \in G$. The diagonal entries of the matrix of $\rho_X(g)$ expressed in the basis $B := \{e_x \mid x \in X\}$ are:

$$\Big(\big(\rho_X(g)\big)_B\Big)_{xx} = \begin{cases} 1 & \text{if } g\cdot x = x \\ 0 & \text{if } g \cdot x \neq x \end{cases} \qquad \forall\, x \in X\,.$$

Hence taking traces, we get $\chi_X(g) = \sum_{x\in X} \Big(\big(\rho_X(g)\big)_B\Big)_{xx} = |\,\mathrm{Fix}_X(g)|$. ■

For the action of G on itself by left multiplication, by Example 1(d), $\rho_X = \rho_{\mathrm{reg}}$ is the regular representation of G. In this case, we obtain the values of the *regular character*.

Corollary 10.2 (*The regular character*)

Let χ_{reg} denote the character of the regular representation ρ_{reg} of G. Then

$$\chi_{\mathrm{reg}}(g) = \begin{cases} |G| & \text{if } g = 1_G, \\ 0 & \text{otherwise.}\end{cases}$$

Proof: This follows immediately from Proposition 10.1 since $\mathrm{Fix}_G(1_G) = G$ and $\mathrm{Fix}_G(g) = \varnothing$ for every $g \in G\setminus\{1_G\}$. ■

Theorem 10.3 (*Decomposition of the regular representation*)

The multiplicity of an irreducible $\mathbb{C}$-representation of G as a constituent of ρ_{reg} equals its degree. In other words,

$$\chi_{\mathrm{reg}} = \sum_{\chi\in\mathrm{Irr}(G)} \chi(1)\chi\,.$$

Proof: By Corollary 9.3 we have $\chi_{\mathrm{reg}} = \sum_{\chi\in\mathrm{Irr}(G)} \langle \chi_{\mathrm{reg}}, \chi\rangle_G\, \chi$, where for each $\chi \in \mathrm{Irr}(G)$,

$$\langle \chi_{\mathrm{reg}}, \chi\rangle_G = \frac{1}{|G|}\sum_{g\in G} \underbrace{\chi_{\mathrm{reg}}(g)}_{\substack{=\delta_{1g}|G| \\ \text{by Cor. 10.2}}}\ \overline{\chi(g)} = \frac{|G|}{|G|}\chi(1) = \chi(1)\,.$$

The claim follows. ■

Remark 10.4

In particular, the theorem tells us that each irreducible $\mathbb{C}$-representation (considered up to equivalence) occurs with multiplicity at least one in a decomposition of the regular representation into irreducible subrepresentations.

Corollary 10.5 (*Degree formula*)

The order of the group G is given in terms of its irreducible character by the formula

$$|G| = \sum_{\chi \in \mathrm{Irr}(G)} \chi(1)^2 .$$

Proof: Evaluating the regular character at $1 \in G$ yields

$$|G| = \chi_{\mathrm{reg}}(1) = \sum_{\chi \in \mathrm{Irr}(G)} \chi(1)\chi(1) = \sum_{\chi \in \mathrm{Irr}(G)} \chi(1)^2 .$$

■

Exercise 10.6 (*Exercise 13(b), Sheet 4*)

Use the degree formula to give a second proof of Proposition 6.1. In other words, prove that if G is a finite abelian group, then

$$\mathrm{Irr}(G) = \{\text{linear characters of } G\} .$$