Representation Theory

Lectured by S. Martin

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Examples Sheets
REPRESENTATION THEORY (D) 24 lectures, Lent term

Linear Algebra, and Groups, Rings and Modules are essential.

Representations of finite groups

Characters
Determination of a representation by its character. The group algebra, conjugacy classes, and orthogonality relations. Regular representation. Induced representations and the Frobenius reciprocity theorem. Mackey’s theorem. \[12\]

Arithmetic properties of characters
Divisibility of the order of the group by the degrees of its irreducible characters. Burnside’s $p^aq^b$ theorem. \[2\]

Tensor products
Tensor products of representations. The character ring. Tensor, symmetric and exterior algebras. \[3\]

Representations of $S^1$ and $SU_2$
The groups $S^1$ and $SU_2$, their irreducible representations, complete reducibility. The Clebsch-Gordan formula. *Compact groups.* \[4\]

Further worked examples
The characters of one of $GL_2(F_q)$, $S_n$ or the Heisenberg group. \[3\]

Appropriate books


Representation Theory

This is the theory of how groups act as groups of transformations on vector spaces.

- group (usually) means finite group.
- vector spaces are finite-dimensional and (usually) over $\mathbb{C}$.

1. Group Actions

- $F$ a field – usually $F = \mathbb{C}$ or $\mathbb{R}$ or $\mathbb{Q}$: ordinary representation theory;
  - sometimes $F = \mathbb{F}_p$ or $\overline{\mathbb{F}_p}$ (algebraic closure): modular representation theory.
- $V$ a vector space over $F$ – always finite-dimensional over $F$.
- $GL(V) = \{ \theta : V \rightarrow V, \theta \text{ linear, invertible} \}$ – group operation is composition, identity is 1.

Basic linear algebra

If dim$_F V = n < \infty$, choose a basis $e_1, \ldots, e_n$ over $F$ so that we can identify it with $F^n$.

Then $\theta \in GL(V)$ corresponds to a matrix $A_\theta = (a_{ij}) \in F_{n \times n}$ where $\theta(e_j) = \sum_i a_{ij} e_i$, and $A_\theta \in GL_n(F)$, the general linear group.

(1.1) $GL(V) \cong GL_n(F)$, $\theta \mapsto A_\theta$. (A group isomorphism – check $A_{\theta_1 \theta_2} = A_{\theta_1} A_{\theta_2}$, bijection.)

Choosing different bases gives different isomorphisms to $GL_n(F)$, but:

(1.2) Matrices $A_1, A_2$ represent the same element of $GL(V)$ with respect to different bases if/when they are conjugate/similar, viz. there exists $X \in GL_n(F)$ such that $A_2 = X A_1 X^{-1}$.

Recall the trace of $A$, $\text{tr}(A) = \sum_i a_{ii}$ where $A = (a_{ij}) \in F_{n \times n}$.

(1.3) $\text{tr}(XAX^{-1}) = \text{tr}(A)$, hence define $\text{tr}(\theta) = \text{tr}(A)$, independent of basis.

(1.4) Let $\alpha \in GL(V)$ where $V$ is finite-dimensional over $\mathbb{C}$ and $\alpha$ is idempotent, i.e. $\alpha^m = \text{id}$, some $m$. Then $\alpha$ is diagonalisable. (Proof uses Jordan blocks – see Telemann p.4.)

Recall End$(V)$, the endomorphism algebra, is the set of all linear maps $V \rightarrow V$ with natural addition of linear maps, and the composition as ‘multiplication’.

(1.5) Proposition. Take $V$ finite-dimensional over $\mathbb{C}$, $\alpha \in \text{End}(V)$. Then $\alpha$ is diagonalisable iff there exists a polynomial $f$ with distinct linear factors such that $f(\alpha) = 0$.

Recall in (1.4), $\alpha^m = \text{id}$, so take $f = X^m - 1 = \prod_{j=0}^{m-1}(X - \omega^j)$, where $\omega = e^{2\pi i/n}$.

Proof of (1.5). $f(X) = (X - \lambda_1) \ldots (X - \lambda_k)$.

Let $f_j(X) = \frac{(X - \lambda_1) \ldots (X - \lambda_j)}{(\lambda_j - \lambda_1) \ldots (\lambda_j - \lambda_k)} \ldots (X - \lambda_k)$

So $1 = \sum f_j(X)$. Put $V_j = f_j(\alpha)V$. The $f_j(\alpha)$ are orthogonal projections, and $V = \bigoplus V_j$ with $V_j \subseteq V(\lambda_j)$ the $\lambda_k$-eigenspace.  

$\square$
Given an action of $G$ on $X$. Proof. For mutation representation $g \in G$.

**Basic group theory**

(1.6) **Symmetric group.** $S_n = \text{Sym}(X_n)$ on the set $X_n = \{1, \ldots, n\}$, is the set of all permutations (bijections $X_n \to X_n$) of $X_n$. $|S_n| = n!$

**Alternating group.** $A_n$ on $X_n$, is the set of products of an even number of transpositions $(ij) \in S_n$. (*$A_n$ is mysterious. Results true for $S_n$ usually fail for $A_n$!*)

(1.7) **Cyclic group** of order $n$, $C_n = \{x : x^n = 1\}$. E.g., $\mathbb{Z}/n\mathbb{Z}$ under $+$. It’s also the group of rotations, centre 0, of the regular $n$-gon in $\mathbb{R}^2$. And also the group of $n$th roots of unity in $\mathbb{C}$ (living in $GL_1(\mathbb{C})$).

(1.8) **Dihedral group.** $D_{2m}$ of order $2m$. $D_{2m} = \{x, y : x^m = y^2 = 1, yxy^{-1} = x^{-1}\}$.

Can think of this as the set of rotations and reflections preserving a regular $m$-gon (living in $GL_2(\mathbb{R})$). E.g., $D_8$, of the square.

(1.9) **Quaternion group, $Q_8 = \{x, y : x^4 = 1, y^2 = x^2, yxy^{-1} = x^{-1}\}$** of order 8.

(*Often used as a counterexample to dihedral results.*)

In $GL_2(\mathbb{C})$, can put $x = \begin{pmatrix} i & 0 \\ 0 & -i \end{pmatrix}$, $y = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$.

(1.10) The **conjugacy class** of $g \in G$ is $C_G(g) = \{xgx^{-1} : x \in G\}$.

Then $|C_G(g)| = |G : C_G(g)|$, where $C_G(g) = \{x \in G : gx = g\}$ is the **centraliser** of $g \in G$.

**Definition.** $G$ a group, $X$ a set. $G$ acts on $X$ if there exists a map $*: G \times X \to X$, $(g, x) \mapsto g \ast x$, written $gx$ for $g \in G, x \in X$, such that:

- $1x = x$ for all $x \in X$
- $(gh)x = g(hx)$ for all $g, h \in G, x \in X$.

Given an action of $G$ on $X$, we obtain a homomorphism $\theta: G \to \text{Sym}(X)$ called the **permutation representation** of $G$.

**Proof.** For $g \in G$, the function $\theta_g : X \to X$, $x \mapsto gx$, is a permutation (inverse is $\theta_{g^{-1}}$). Moreover, for all $g_1, g_2 \in G$, $\theta_{g_1} \circ \theta_{g_2} = \theta_{g_1g_2}$ since $(g_1g_2)x = g_1(g_2x)$ for $x \in X$. □

In this course, $X$ is often a finite-dimensional vector space, and the action is **linear**, viz: $g(v_1 + v_2) = gv_1 + gv_2, g(\lambda v) = \lambda gv$ for all $v, v_1, v_2 \in V = X, g \in G, \lambda \in F$.  

(1.4*) In fact, a finite family of commuting separately diagonalisable automorphisms of a $\mathbb{C}$-space can be simultaneously diagonalised.
2. Linear Representations

$G$ a finite group. $F$ a field, usually $\mathbb{C}$.

**Definition.** Let $V$ be a finite-dimensional vector space over $F$. A (linear) representation of $G$ on $V$ is a homomorphism $\rho : G \to GL(V)$.

We write $\rho_g$ for $\rho_V(g)$. So for each $g \in G$, $\rho_g \in GL(V)$ and $\rho_{g_1g_2} = \rho_{g_1}\rho_{g_2}$.

The dimension or degree of $\rho$ is $\dim_F V$.

**Example.** Given any group $G$, let $\rho : G \to GL(V)$ be a representation of $G$ on $V$. Then $\rho(g) : V \to V$ is a linear representation of $G$. Conversely, given a representation $G \to GL(V)$, we have a linear action of $G$ on $V$ via $g \cdot v = \rho(g)v$, for all $v \in V, \ g \in G$.

**Example.** Given any group $G$, take $V = F$ (the 1-dimensional space) and $\rho : G \to GL(V)$, $g \mapsto (id : F \to F)$. This is known as the **trivial/principal** representation. So deg $\rho = 1$.

**Example.** $G = C_4 = \langle x : x^4 = 1 \rangle$.

Let $n = 2$ and $F = \mathbb{C}$. Then $R : x \mapsto X$ (some matrix $X$) will determine all $x^j \mapsto X^j$. We need $X^4 = I$. We can take $X$ diagonal with diagonal entries $\in \{\pm 1, \pm i\}$ (16 choices). Or we can take $X$ not diagonal, then it will be isomorphic to some diagonal matrix, by (1.4).

**Definition.** Fix $G,F$. Let $V,V'$ be $F$-spaces and $\rho : G \to GL(V)$, $\rho' : G \to GL(V')$ be representations of $G$. The linear map $\phi : V \to V'$ is a **$G$-homomorphism** if

$$\phi \rho(g) = \rho'(g)\phi$$

for all $g \in G$.

The square commutes.
We say \( \phi \) intertwines \( \rho, \rho' \).

We write \( \text{Hom}_G(V, V') \) for the \( F \)-space of all of these.

We say that \( \phi \) is a \textit{G-isomorphism} if also \( \phi \) is bijective; if such a \( \phi \) exists we say that \( \rho, \rho' \) are \textit{isomorphic}. If \( \phi \) is a \( G \)-isomorphism, we write \((*)\) as \( \rho' = \rho \phi \phi^{-1} \) (meaning \( \rho'(g) = \phi \rho(g) \phi^{-1} \) for all \( g \in G \)).

\((2.9)\) The relation of being isomorphic is an equivalence relation on the set of all linear representations of \( G \) (over \( F \)).

**Remark.** The basic problem of representation theory is to classify all representations of a given group \( G \) up to isomorphisms. Good theory exists for finite groups over \( \mathbb{C} \), and for compact topological groups.

\((2.10)\) If \( \rho, \rho' \) are isomorphic representations, they have the same dimension. Converse is false: in \( C_4 \) there are four non-isomorphic 1-dimensional representations. If \( \omega = e^{2\pi i/4} \) then we have \( \rho_i(\omega^i) = \omega^{ij} \) (\( 0 \leq i \leq 3 \)).

\((2.11)\) Given \( G, V \) over \( F \) of dimension \( n \) and \( \rho: G \to GL(V) \). Fix a basis \( B \) for \( V \); we get a linear isomorphism \( \phi: V \to F^n, v \mapsto [v]_B \).

Get a representation \( \rho' : G \to GL(F^n) \) isomorphic to \( \rho \).

\[
\begin{align*}
V & \xrightarrow{\rho} V \\
\phi & \downarrow \quad \downarrow \phi \\
F^n & \xrightarrow{\rho'} F^n
\end{align*}
\]

\((2.12)\) In terms of matrix representations, \( R: G \to GL_n(F), R': G \to GL_n(F) \) are \textit{G-isomorphic} if there exists a (non-singular) matrix \( X \in GL_n(F) \) with \( R'(g) = XR(g)X^{-1} \) (for all \( g \in G \)).

In terms of \( G \)-actions, the actions of \( G \) on \( V, V' \) are \( G \)-isomorphic if there is an isomorphism \( \phi : V \to V' \) such that \( g \phi(v) = \phi(gv) \) for all \( g \in G, v \in V \).

**Subrepresentations**

\((2.13)\) Let \( \rho : G \to GL(V) \) be a representation of \( G \). Say that \( W \subseteq V \) is a \( G \)-\textit{subspace} if it’s a subspace and is \( \rho(G) \)-invariant, i.e. \( \rho_g(W) \subseteq W \) for all \( g \in G \). E.g., \( \{0\} \) and \( V \).

Say \( \rho \) is \textit{irreducible}, or \textit{simple}, if there is no proper \( G \)-subspace.

\((2.14)\) **Example.** Any 1-dimensional representation of \( G \) is irreducible. (But not conversely: e.g. \( D_4 \) has a 2-dimensional \( \mathbb{C} \)-irreducible representation.)

\((2.15)\) In definition \((2.13)\) if \( W \) is a \( G \)-subspace then the corresponding map \( G \to GL(W) \), \( g \mapsto \rho(g)|_W \) is a representation of \( G \), a \textit{subrepresentation} of \( \rho \).

\((2.16)\) **Lemma.** \( \rho : G \to GL(V) \) a representation. If \( W \) is a \( G \)-subspace of \( V \) and if \( B = \{v_1, \ldots, v_n\} \) is a basis of \( V \) containing the basis \( \{v_1, \ldots, v_m\} \) of \( W \), then the matrix of \( \rho(g) \) with respect to \( B \) is (with the top-left \(* \) being \( m \times m \))\n
\[
\begin{pmatrix}
* & * \\
0 & *
\end{pmatrix}
\]

(for each \( g \in G \))
(2.17) Examples

(i) (2.10) revisited. The irreducible representations of \( C_4 = \langle x : x^4 = 1 \rangle \) are all 1-dimensional, and four of these are \( x \mapsto i, x \mapsto -1, x \mapsto -i, x \mapsto 1 \).

(The two \( x \mapsto \pm i \) are faithful, since they have trivial kernel.)

In general, \( C_m = \langle x : x^m = 1 \rangle \) has precisely \( m \) irreducible complex representations, all of degree 1. Put \( \omega = e^{2\pi i/m} \in \mu_m \) and define \( \rho_k : x^j \mapsto \omega^j k \) (\( 0 \leq j, k \leq m - 1 \)).

It turns out that all irreducible complex representations of a finite abelian group are 1-dimensional: (1.4*) or see (4.4) below.

(ii) \( G = D_6 = \langle x, y : x^3 = y^2 = 1, yxy^{-1} = x^{-1} \rangle \), the smallest non-abelian finite group. \( G \cong S_3 \) (generated by a 3-cycle and a 2-cycle).

\( G \) has the following irreducible complex representations:

\[
\begin{align*}
\text{2 of degree 1:} & \quad \rho_1 : x \mapsto 1, y \mapsto 1 \\
& \rho_2 : x \mapsto 1, y \mapsto -1 \\
\text{1 of degree 2:} & \quad \rho_3 : x \mapsto \begin{pmatrix} \omega & 0 \\ 0 & \omega^{-1} \end{pmatrix}, y \mapsto \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \text{where } \omega = e^{2\pi i/3} \in \mu_3
\end{align*}
\]

This follows easily later on. For now, by brute force...

Define \( u_0 = 1 + x + x^2 \), \( v_0 = u_0 y \),
\( u_1 = 1 + \omega x + \omega^2 x^2 \), \( v_1 = u_1 y \),
\( u_2 = 1 + \omega^2 x + \omega x^2 \), \( v_2 = u_2 y \).

Check easily \( xu_1 = x + \omega^2 x^2 + \omega = \omega u_1 \), and in general \( xu_i = \omega^i u_i \) (\( 0 \leq i \leq 2 \)). (I.e., in the action of \( x, u_i \) is an eigenvector, of eigenvalue \( \omega^i \).) So \( \langle u_i \rangle, \langle v_i \rangle \) are \( \mathbb{C}\langle x \rangle \)-modules.

Also: \( yu_0 = v_0 \), \( yu_2 = v_2 \), \( yu_1 = v_1 \), \( yv_0 = u_0 \), \( yv_1 = u_1 \), \( yv_2 = u_2 \).

So \( \langle u_0, v_0 \rangle, \langle u_1, v_2 \rangle, \langle u_2, v_1 \rangle \) are \( \mathbb{C}\langle y \rangle \)-modules, and hence are all \( \mathbb{C}G \)-submodules.

Note, \( U_3 = \langle u_1, v_2 \rangle, U_4 = \langle u_2, v_1 \rangle \) are irreducible and \( \langle u_0, v_0 \rangle \) has \( U_1 = \langle u_0 + v_0 \rangle \) and \( U_2 = \langle u_0 - v_0 \rangle \) as \( \mathbb{C}G \)-submodules.

Moreover, \( CD_6 = U_1 \oplus U_2 \oplus U_3 \oplus U_4 \).

(iii) \( G = D_8 = \langle x, y : x^4 = y^2 = 1, yxy^{-1} = x^{-1} \rangle \), the rotations/reflections of a square. \( G \leq S_4 \). See (1.8) with \( m = 4 \).

\( G \) has the following irreducible complex representations:

\[
\begin{align*}
\text{4 of degree 1:} & \quad \rho_0 : x \mapsto 1, y \mapsto 1 \quad \text{(trivial)} \\
& \rho_1 : x \mapsto 1, y \mapsto -1 \\
& \rho_2 : x \mapsto -1, y \mapsto 1 \\
& \rho_3 : x \mapsto -1, y \mapsto -1 \\
\text{1 of degree 2:} & \quad \rho_4 : x \mapsto \begin{pmatrix} i & 0 \\ 0 & -i \end{pmatrix}, y \mapsto \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad \text{(up to isomorphism)}
\end{align*}
\]
By considering the effect of \( y \) on eigenvectors of \( x \), we’ll show that any irreducible representation of \( G \) is isomorphic to one of the \( \rho_i \). This is easy to do later. Here, let \( V \) be some irreducible \( G \)-space.

Under the action of \( x \), we have

\[
V|_x = V_1 \oplus V_{-1} \oplus V_i \oplus V_{-i}
\]

where \( V_{\lambda} = \{ v \in V : xv = \lambda v \} \).

For the \( y \)-action: if \( xv = v \) then \( yv \in V_1 \), since \( x(yv) = yx^{-1}v = yv \); similarly if \( xv = -v \) then \( yv \in V_{-1} \), since \( x(yv) = yx^{-1}v = -yv \).

So, if \( V \) is irreducible and \( V_1 \neq 0 \) or \( V_{-1} \neq 0 \), then \( V \) is 1-dimensional (so one of the \( \rho_j \), \( 0 \leq j \leq 3 \)).

Taking \( v \in V_1 \), we have \( xv = v \), and \( yv \) is either \( v \) or \( -v \).

Taking \( v \in V_{-1} \), we have \( xv = -v \), and \( yv \) is either \( v \) or \( -v \). \( \) \( \) \( \) So, four cases.

Final case: \( V = V_i \oplus V_{-i} \).

Let \( v \in V_i \), i.e. \( xv = iv \). Then \( yv \in V_{-i} \), since \( x(yv) = yx^{-1}v = -iyv \), and vice versa.

Clearly \( \langle v, yv \rangle \) is \( G \)-invariant, so \( V = \langle v, yv \rangle \) as \( V \) is irreducible. Taking basis \( \{ v, yv \} \) we have \( x, y \) acting as in \( \rho_i \) (with respect to this basis).

See James & Liebeck, p. 94, and also Example Sheet 1.

(2.18) Definition. We say that \( \rho : G \to GL(V) \) is **decomposable** if there are \( G \)-invariant subspaces \( U, W \) with \( V = U \oplus W \). Say \( \rho \) is a direct sum \( \rho_U \oplus \rho_W \). If no such exists, we say \( \rho \) is **indecomposable**.

\( (U, W \) must have \( G \)-actions on them, not just ordinary vector subspaces.)

(2.19) Lemma. Suppose \( \rho : G \to GL(V) \) is a decomposition with \( G \)-invariant decomposition \( V = U \oplus W \). If \( B = \{ u_1, \ldots, u_k, w_1, \ldots, w_l \} \) consisting of a basis \( B_1 \) of \( U \) and \( B_2 \) of \( W \), then with respect to \( B \),

\[
\rho(g) = \begin{bmatrix}
\ast & 0 \\
0 & \ast
\end{bmatrix} = \begin{bmatrix}
[\rho_U(g)]_{B_1} & 0 \\
0 & [\rho_W(g)]_{B_2}
\end{bmatrix}
\]

(2.20) Definition. \( \rho : G \to GL(V), \rho' : G \to GL(V') \). The direct sum of \( \rho, \rho' \) is

\[
\rho \oplus \rho' : G \to GL(V \oplus V'), \quad (\rho \oplus \rho')(g)(v_1 + v_2) = \rho(g)v_1 + \rho'(g)v_2
\]

– a block diagonal action.

For matrix representations, \( R : G \to GL_n(F), R' : G \to GL_{n'}(F) \), define

\[
R \oplus R' : G \to GL_{n+n'}(F), \quad g \mapsto \begin{bmatrix}
R(g) & 0 \\
0 & R'(g)
\end{bmatrix}, \quad \forall g \in G.
\]
3. Complete Reducibility and Maschke’s Theorem

$G, F$ as usual.

(3.1) Definition. The representation $\rho : G \to GL(V)$ is completely reducible, or semisimple, if it is a direct sum of irreducible representations.

Evidently, simple $\Rightarrow$ completely reducible, but not conversely.

(3.2) Examples. Not all representations are completely reducible.

(i) $G = \{ \begin{pmatrix} 1 & n \\ 0 & 1 \end{pmatrix} : n \in \mathbb{Z} \}$, $V = \mathbb{C}^2$, natural action ($gv$ is matrix multiplication).

$V$ is not completely reducible. (Note $G$ not finite.)

(ii) $G = \mathbb{F}_p, F = \mathbb{F}_p, x_j \mapsto \begin{pmatrix} 1 & 0 \\ j & 1 \end{pmatrix}$ $(0 \leq j \leq p - 1)$ defines a representation $G \to GL_2(F)$.

$V = \langle v_1, v_2 \rangle$ where $x_jv_1 = v_1, x_jv_2 = jv_1 + v_2$. Define $W = \langle v_1 \rangle$.

Then $W$ is an $FC_p$-module but there is no $X$ s.t. $V = W \oplus X$. (Note $F \neq \mathbb{R}, \mathbb{C}$.)

(3.3) Theorem (Complete Reducibility Theorem). Every finite-dimensional representation of a finite group over a field of characteristic 0 is completely reducible.

Enough to prove the following.

(3.4) Theorem (Maschke’s Theorem). $G$ finite, $\rho : G \to GL(V)$ with $V$ an $F$-space, $\text{char } F = 0$. If $W$ is a $G$-subspace of $V$ then there exists a $G$-subspace $U$ of $V$ such that $V = W \oplus U$ (a direct sum of $G$-subspaces).

Note. The proof below also works for $(\text{char } F, |G|) = 1$.

Proof 1. Let $W'$ be any vector space complement of $W$ in $V$, i.e. $V = W \oplus W'$. Let $q : V \to W'$ be the projection of $V$ onto $W'$ along $W''$, i.e. if $v = w + w'$ then $q(v) = w$.

Define $\overline{q} : v \mapsto \frac{1}{|G|} \sum_{g \in G} \rho(g)q(\rho(g^{-1})v)$, the ‘average of $q$ over $G$’.

Drop the $\rho's$ – i.e. write $\rho(g)q(\rho(g^{-1})v)$ as $gq(g^{-1}v)$.

Claim (i). $\overline{q} : V \to W$.

For $v \in V$, $q(g^{-1}v) \in W$ and $gW \subseteq W$ (as $W$ is $g$-invariant).

Claim (ii). $\overline{q}(w) = w$ for $w \in W$.

$$\overline{q}(w) = \frac{1}{|G|} \sum_{g \in G} gq(g^{-1}w) = \frac{1}{|G|} \sum_{g \in G} g(g^{-1}w) = \frac{1}{|G|} \sum_{g \in G} w = w.$$ 

So (i), (ii) $\Rightarrow \overline{q}$ projects $V$ onto $W$.
Claim (iii). If \( h \in G \) then \( h\overline{q}(v) = \overline{q}(hv) \) (for \( v \in V \)).

\[
\begin{align*}
    h\overline{q}(v) &= \frac{1}{|G|} \sum_{g \in G} g q(g^{-1}v) = \frac{1}{|G|} \sum_{g \in G} h q q(g^{-1}v) = \frac{1}{|G|} \sum_{g \in G} (hg) q((hg)^{-1}hv) \\
    &= \frac{1}{|G|} \sum_{g' \in G} g' q(g'^{-1}(hv)) = \overline{q}(hv).
\end{align*}
\]

Claim (iv). \( \ker \overline{q} \) is \( G \)-invariant.

If \( v \in \ker \overline{q} \) and \( h \in G \), then \( h\overline{q}(v) = 0 = \overline{q}(hv) \), so \( hv \in \ker \overline{q} \).

Then \( V = \text{im} \overline{q} \oplus \ker \overline{q} = W \oplus \ker \overline{q} \) is a \( G \)-subspace decomposition. \( \square \)

Remark. Complements are not necessarily unique.

The second proof uses inner products, hence we need to take \( F = \mathbb{C} \) (or \( \mathbb{R} \)), and it can be generalised to compact groups (chapter 15).

Recall for \( V \) a \( \mathbb{C} \)-space, \( \langle , \rangle \) is a \( \mathbb{C} \)-inner product if

(a) \( \langle w, v \rangle = \overline{\langle v, w \rangle} \) for all \( v, w \)

(b) linear in LHS

(c) \( \langle v, v \rangle > 0 \) if \( v \neq 0 \)

Additionally, \( \langle , \rangle \) is \( G \)-invariant if

(d) \( \langle gv, gw \rangle = \langle v, w \rangle \) for all \( v, w \in V, g \in G \)

Note that if \( W \) is a \( G \)-subspace of \( V \) (with \( G \)-invariant inner product) then \( W^\perp \) is also \( G \)-invariant and \( V = W \oplus W^\perp \).

Proof. Want: for all \( v \in W^\perp \), for all \( g \in G \), we have \( gv \in W^\perp \).

Now, \( v \in W^\perp \iff \langle v, w \rangle = 0 \) for all \( w \in W \). Thus \( \langle gv, gw \rangle = 0 \) for all \( g \in G, w \in W \).

Hence \( \langle gv, w' \rangle = 0 \) for all \( w' \in W \) since we can take \( w = g^{-1}w' \) by \( G \)-invariance of \( W \).

Hence \( gv \in W^\perp \) since \( g \) was arbitrary. \( \square \)

Hence if there is a \( G \)-invariant inner product on any complex \( G \)-space, we get:

(3.4') (Weyl’s Unitary Trick). Let \( \rho \) be a complex representation of the finite group \( G \) on the \( \mathbb{C} \)-space \( V \). There is a \( G \)-invariant inner product on \( V \) (whence \( \rho(G) \) is conjugate to a subgroup of \( U(V) \), the unitary group on \( V \), i.e. \( \rho(g)^* = \rho(g^{-1}) \)).

Proof. There is an inner product on \( V \): take basis \( e_1, \ldots, e_n \), and define \( \langle e_i, e_j \rangle = \delta_{ij} \), extended sesquilinearly. Now define \( \langle v, w \rangle = \frac{1}{|G|} \sum_{g \in G} (gv, gw) \).

Claim. \( \langle , \rangle \) is sesquilinear, positive definite, and \( G \)-invariant.

If \( h \in G \), \( \langle hv, hw \rangle = \frac{1}{|G|} \sum_{g \in G} ((gh)v, (gh)w) = \frac{1}{|G|} \sum_{g' \in G} (g'v, g'w) = \langle v, w \rangle \). \( \square \)
(3.5) (The (left) regular representation of $G$.) Define the group algebra of $G$ to be the $F$-space $FG = \text{span}\{e_g : g \in G\}$.

There is a $G$-linear action: for $h \in G$, define $h\left(\sum_g a_g e_g\right) = \sum_g a_g e_{hg} = \sum_{g'} a_{h^{-1}g} e_{g'}$.

$\rho_{\text{reg}}$ is the corresponding representation – the regular representation of $G$.

This is faithful of dimension $|G|$.

It turns out that every irreducible representation of $G$ is a subrepresentation of $\rho_{\text{reg}}$.

(3.6) Proposition. Let $\rho$ be an irreducible representation of the finite group $G$ over a field of characteristic 0. Then $\rho$ is isomorphic to a subrepresentation of $\rho_{\text{reg}}$.

Proof. Take $\rho : G \to GL(V)$, irreducible, and let $0 \neq v \in V$.

Let $\theta : FG \to V$, $\sum_g a_g e_g \mapsto \sum_g a_ggv$ (a $G$-homomorphism).

Now, $V$ is irreducible and so $\text{im} \theta = V$ (since $\text{im} \theta$ is a $G$-subspace). Also $\ker \theta$ is a $G$-subspace of $FG$. Let $W$ be a $G$-complement of $\ker \theta$ in $FG$ (using (3.4)), so that $W < FG$ is a $G$-subspace and $FG = \ker \theta \oplus W$.

Hence $W \cong FG/\ker \theta \cong \text{im} \theta = V$. $\Box$

More generally,

(3.7) Definition. Let $F$ be a field, and let $G$ act on a set $X$. Let $FX = \text{span}\{e_x : x \in X\}$, with $G$-action $g \left(\sum_{x \in X} a_x e_x\right) = \sum a_x e_{gx}$.

So we have a $G$-space $FX$. The representation $G \to GL(V)$ with $V = FX$ is the corresponding permutation representation.
4. Schur’s Lemma

(4.1) Theorem (‘Schur’s Lemma’). (a) Assume $V, W$ are irreducible $G$-spaces (over a field $F$). Then any $G$-homomorphism $\theta : V \rightarrow W$ is either 0 or an isomorphism.

(b) Assume $F$ is algebraically closed and let $V$ be an irreducible $G$-space. Then any $G$-endomorphism $\theta : V \rightarrow V$ is a scalar multiple of the identity map $\text{id}_V$ (a homothety).

Proof. (a) Let $\theta : V \rightarrow W$ be a $G$-homomorphism. Then $\ker \theta$ is a $G$-subspace of $V$, and since $V$ is irreducible, either $\ker \theta = 0$ or $\ker \theta = V$. And $\text{im} \theta$ is a $G$-subspace of $W$, so as $W$ is irreducible, $\text{im} \theta$ is either 0 or $W$. Hence either $\theta = 0$ or $\theta$ is injective and surjective, so $\theta$ is an isomorphism.

(b) Since $F$ is algebraically closed, $\theta$ has an eigenvalue $\lambda$. Then $\theta - \lambda \text{id}$ is a singular $G$-endomorphism on $V$, so must be 0, so $\theta = \lambda \text{id}$.

Recall from (2.8) the $F$-space $\text{Hom}_G(V, W)$ of all $G$-homomorphisms $V \rightarrow W$. Write $\text{End}_G(V)$ for the endomorphism algebra $\text{Hom}_G(V, V)$.

(4.2) Corollary. If $V, W$ are irreducible complex $G$-spaces, then

$$\dim \mathbb{C} \text{Hom}_G(V, W) = \begin{cases} 1 & \text{if } V, W \text{ are } G\text{-isomorphic} \\ 0 & \text{otherwise} \end{cases}$$

Proof. If $V, W$ are not isomorphic then the only $G$-homomorphism $V \rightarrow W$ is 0 by (4.1). Assume $V \cong_G W$ and $\theta_1, \theta_2 \in \text{Hom}_G(V, W)$, both $\neq 0$. Then $\theta_2$ is invertible by (4.1) and $\theta_2^{-1}\theta_1 \in \text{Hom}_G(V, V)$. So $\theta_2^{-1}\theta_1 = \lambda \text{id}$ for some $\lambda \in \mathbb{C}$. Then $\theta_1 = \lambda \theta_2$. □

(4.3) Corollary. If $G$ has a faithful complex irreducible representation then $Z(G)$ is cyclic.

Remark. The converse is false. (See examples sheet 1, question 11.)

Proof. Let $\rho : G \rightarrow GL(V)$ be a faithful irreducible complex representation. Let $z \in Z(G)$, so $zg = gz$ for all $g \in G$.

Consider the map $\phi_z : v \mapsto zv$ for $v \in V$. This is a $G$-endomorphism on $V$, hence is multiplication by a scalar $\mu_z$, say (by Schur).

Then the map $Z(G) \rightarrow \mathbb{C}^\times$, $z \mapsto \mu_z$, is a representation of $Z$ and is faithful (since $\rho$ is). Thus $Z(G)$ is isomorphic to a finite subgroup of $\mathbb{C}^\times$, hence is cyclic. □

Applications to abelian groups

(4.4) Corollary. The irreducible complex representations of a finite abelian group $G$ are all 1-dimensional.

Proof. Either (1.4*) to invoke simultaneous diagonalisation: if $v$ is an eigenvector for each $g \in G$ and if $V$ is irreducible, then $V = \langle v \rangle$.

Or let $V$ be an irreducible complex representation. For $g \in G$, the map $\theta_g : V \rightarrow V$, $v \mapsto gv$, is a $G$-endomorphism of $V$ and, as $V$ is irreducible, $\theta_g = \lambda g \text{id}$ for some $\lambda_g \in \mathbb{C}$. Thus $gv = \lambda_g v$ for any $g$. Thus, as $V$ is irreducible, $V = \langle v \rangle$ is 1-dimensional. □

Remark. This fails on $\mathbb{R}$. E.g., $C_3$ has two irreducible real representations: one of dimension 1, one of dimension 2. (See sheet 1, question 12.)
Recall that any finite abelian group $G$ is isomorphic to a product of cyclic groups, e.g. $C_6 \cong C_2 \times C_3$. In fact, it can be written as a product of $C_p^\alpha$ for various primes $p$ and $\alpha \geq 1$, and the factors are uniquely determined up to ordering.

(4.5) Proposition. The finite abelian group $G = C_{n_1} \times \ldots \times C_{n_r}$ has precisely $|G|$ irreducible complex representations, as described below.

Proof. Write $G = \langle x_1 \rangle \times \ldots \times \langle x_r \rangle$ where $o(x_j) = n_j$. Suppose $\rho$ is irreducible – so by (4.4) it’s 1-dimensional, $\rho : G \to \mathbb{C}^\times$.

Let $\rho(1, \ldots, 1, x_j, 1, \ldots, 1) = \lambda_j \in \mathbb{C}^\times$. Then $\lambda_j^{n_j} = 1$, so $\lambda_j$ is an $n_j^{th}$ root of unity.

Now the values $(\lambda_1, \ldots, \lambda_r)$ determine $\rho$, as $\rho(x_1^{i_1} \ldots x_r^{i_r}) = \lambda_1^{i_1} \ldots \lambda_r^{i_r}$.

Thus $\rho \leftrightarrow (\lambda_1, \ldots, \lambda_r)$ with $\lambda_j^{n_j} = 1$ for all $j$. (And have $n_1 \ldots n_r$ such $r$-tuples, each giving a 1-dimensional representation.

Examples. (a) $G = C_4 = \langle x \rangle$.

<table>
<thead>
<tr>
<th></th>
<th>$1$</th>
<th>$x$</th>
<th>$x^2$</th>
<th>$x^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho_1$</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$\rho_2$</td>
<td>1</td>
<td>$i$</td>
<td>$-1$</td>
<td>$i$</td>
</tr>
<tr>
<td>$\rho_3$</td>
<td>1</td>
<td>$-1$</td>
<td>1</td>
<td>$-1$</td>
</tr>
<tr>
<td>$\rho_4$</td>
<td>1</td>
<td>$-i$</td>
<td>$-1$</td>
<td>$i$</td>
</tr>
</tbody>
</table>

(b) $G = V_4 = \langle x_1 \rangle \times \langle x_2 \rangle \cong C_2 \times C_2$.

<table>
<thead>
<tr>
<th></th>
<th>$x_1$</th>
<th>$x_2$</th>
<th>$x_1x_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho_1$</td>
<td>1</td>
<td>1</td>
<td>1</td>
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<tr>
<td>$\rho_2$</td>
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<tr>
<td>$\rho_3$</td>
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<td>$-1$</td>
<td>1</td>
</tr>
<tr>
<td>$\rho_4$</td>
<td>1</td>
<td>$-1$</td>
<td>$-1$</td>
</tr>
</tbody>
</table>

Warning. There is no ‘natural’ 1-1 correspondence between the elements of $G$ and the representations of $G$. If you choose an isomorphism $G \cong C_1 \times \ldots \times C_r$, then you can identify the two sets, but it depends on the choice of isomorphism.

** Non-examinable section **

Application to isotypical decompositions

(4.6) Proposition. Let $V$ be a $G$-space over $\mathbb{C}$, and assume $V = U_1 \oplus \ldots \oplus U_n = W_1 \oplus \ldots \oplus W_n$, with all the $U_j, W_k$ irreducible $G$-spaces. Let $X$ be a fixed irreducible $G$-space. Let $U$ be the sum of all the $U_j$ isomorphic to $X$, and $W$ be the sum of all the $W_j$ isomorphic to $X$.

Then $U = W$, and is known as the isotypical component of $V$ corresponding to $X$. Hence:

$\# U_j$ isomorphic to $X = \# W_k$ isomorphic to $X = (V : X) = \text{multiplicity}$ of $X$ in $V$.

Proof (sketch). Look at $\theta_{jk} : U_j \overset{i_j}{\longrightarrow} V \overset{\pi_k}{\longrightarrow} W_k$, with $W_k \cong X$, where $i_j$ is inclusion and $\pi_k$ is projection. If $U_j \cong X$ then $U_j \subset W_k$ – all the projections to the other $W_\ell$ are 0.

‘Then fiddle around with dimensions, then done.’

/Box
**Proposition.** $(V : X) = \dim_{\mathbb{C}} \text{Hom}_G(V, X)$ for $X$ irreducible, $V$ any $G$-space.

**Proof.** Prove $\text{Hom}_G(W_1 \oplus W_2, X) \cong \text{Hom}_G(W_1, X) \oplus \text{Hom}_G(W_2, X)$, then apply Schur. (Or see James & Liebeck 11.6.)

**Proposition.** $\dim_{\mathbb{C}} \text{Hom}_G(\mathbb{C}G, X) = \dim_{\mathbb{C}} X$.

**Proof.** Let $d = \dim X$, and take a basis $\{e_1, \ldots, e_d\}$ of $X$. Define $\phi_i : \mathbb{C}G \to X$, $g \mapsto ge_i$ $(1 \leq i \leq d)$. Then $\phi_i \in \text{Hom}_G(\mathbb{C}G, X)$ and $\{\phi_1, \ldots, \phi_d\}$ is a basis. (See James & Liebeck 11.8.)

**Remark.** If $V_1, \ldots, V_r$ are all the distinct complex irreducible $G$-spaces then $\mathbb{C}G = n_1 V_1 \oplus \ldots \oplus n_r V_r$ where $n_i = \dim V_i$. Then $|G| = n_1^2 + \ldots + n_r^2$. (See (5.9), or James & Liebeck 11.2.)

Recall (2.17). $G = D_6$, $\mathbb{C}G = U_1 \oplus U_3 \oplus U_3 \oplus U_4$, $\dim \text{Hom}(\mathbb{C}G, U_3) = 2$. (Challenge: find a basis for it.) $U_1$ and $U_2$ occur with multiplicity 1, and $U_3$ occurs with multiplicity 2.

**End of non-examinable section**
5. Character Theory

We want to attach invariants to a representation \( \rho \) of a finite group \( G \) on \( V \). Matrix coefficients of \( \rho(g) \) are basis dependent, so not true invariants.

Take \( F = \mathbb{C} \), and \( G \) finite. \( \rho = \rho_V : G \to GL(V) \), a representation of \( G \).

(5.1) Definition. The character \( \chi_\rho = \chi_V = \chi \) is defined by \( \chi(g) = \text{tr} \rho(g) \) (= \( \text{tr} R(g) \)), where \( R(g) \) is any matrix representation of \( \rho(g) \) with respect to any basis). The degree of \( \chi_V \) is \( \dim V \).

Thus \( \chi \) is a function \( G \to \mathbb{C}^\times \). \( \chi \) is linear if \( \dim V = 1 \), in which case \( \chi \) is a homomorphism \( G \to \mathbb{C}^\times \).

- \( \chi \) is irreducible if \( \rho \) is.
- \( \chi \) is faithful if \( \rho \) is.
- \( \chi \) is trivial (principal) if \( \rho \) is the trivial representation: write \( \chi = 1_G \).

\( \chi \) is a complete invariant in the sense that it determines \( \rho \) up to isomorphism – see (5.7).

(5.2) First properties.

(i) \( \chi_V(1) = \dim V \).
(ii) \( \chi_V \) is a class function, viz it is conjugation invariant, i.e. \( \chi_V(hgh^{-1}) = \chi_V(g) \) for all \( g, h \in G \).

Thus \( \chi_V \) is constant on the conjugacy classes (ccls) of \( G \).
(iii) \( \chi_V(g^{-1}) = \chi_V(g) \).
(iv) For two representations, \( V, W \), have \( \chi_V \oplus \chi_W = \chi_V + \chi_W \).

Proof. (i) \( \text{tr} \, (1) = n \).
(ii) \( \chi(hgh^{-1}) = \text{tr} \, (R_h R_g R_h^{-1}) = \text{tr} \, (R_g) = \chi(g) \).
(iii) \( g \in G \) has finite order, so by (1.4) can assume \( \rho(g) \) is represented by a diagonal matrix \( \begin{bmatrix} \lambda_1 & \cdots & \lambda_n \end{bmatrix} \). Thus \( \chi(g) = \sum \lambda_i \). Now \( g^{-1} \) is represented by \( \begin{bmatrix} \lambda_1^{-1} & \cdots & \lambda_n^{-1} \end{bmatrix} \).

and since \( |\lambda_i| = 1 \) for all \( i \), \( \chi(g^{-1}) = \sum \lambda_i^{-1} = \sum \lambda_i = \chi(g) \).
(iv) Suppose \( V = V_1 \oplus V_2 \). \( \rho_i : G \to GL(V_i) \), \( \rho : G \to GL(V) \). Take bases \( B = B_1 \cup B_2 \) of \( V \), containing bases \( B_i \) of \( V_i \).

With respect to \( B \), \( \rho(g) \) has matrix \( \begin{bmatrix} [\rho_1(g)]_{B_1} & 0 \\ 0 & [\rho_2(g)]_{B_2} \end{bmatrix} \).

So \( \chi(g) = \text{tr} \, (this) = \text{tr} \rho_1(g) + \text{tr} \rho_2(g) = \chi_1(g) + \chi_2(g) \). \( \Box \)

Remark. We see later that \( \chi_1, \chi_2 \) characters of \( G \Rightarrow \chi_1 \chi_2 \) also a character of \( G \). This uses tensor products – see (9.6).

(5.3) Lemma. Let \( \rho : G \to GL(V) \) be a complex representation affording (“which can take”) the character \( \chi \). Then \( |\chi(g)| \leq \chi(1) \), with equality iff \( \rho(g) = \lambda \text{id} \) for some \( \lambda \in \mathbb{C} \), a root of unity. Moreover, \( \chi(g) = \chi(1) \Leftrightarrow g \in \ker \rho \).

Proof. Fix \( g \). W.r.t. a basis of \( V \) of eigenvectors of \( \rho(g) \), the matrix of \( \rho(g) \) is \( \begin{bmatrix} \lambda_1 & \cdots & \lambda_n \end{bmatrix} \).
Hence, $|\chi(g)| = |\sum \lambda_i| \leq \sum |\lambda_i| = 1 = \dim V = \chi(1)$, with equality iff all $\lambda_j$ are equal to $\lambda$, say (using Cauchy-Schwarz). And if $\chi(g) = \chi(1)$ then $\rho(g) = \lambda \id$.

Therefore, $\chi(g) = \lambda \chi(1)$, and so $\lambda = 1$ and $g \in \ker \rho$. \hfill \Box

(5.4) **Lemma.** If $\chi$ is a complex irreducible character of $G$, then so is $\overline{\chi}$, and so is $\varepsilon \chi$ for any linear character $\varepsilon$ of $G$.

**Proof.** If $R : G \to GL_n(\mathbb{C})$ is a complex (matrix) representation then so is $\overline{R} : G \to GL_n(\mathbb{C})$, $g \mapsto \overline{R}(g)$.

Similarly for $R' : g \mapsto \varepsilon(g)R(g)$. Check the details. \hfill \Box

(5.5) **Definition.** $\mathcal{C}(G) = \{ f : G \to \mathbb{C} : f(hgh^{-1}) = f(g) \ \forall h, g \in G \}$, the $\mathbb{C}$-space of class functions. (Where $f_1 + f_2 : g \mapsto f_1(g) + f_2(g)$, $\lambda f : g \mapsto \lambda f(g)$.)

List conjugacy classes as $\mathcal{C}_1(= \{1\})$, $\mathcal{C}_2$, ..., $\mathcal{C}_k$. Choose $g_1(= 1)$, $g_2$, ..., $g_k$ as representatives of the classes.

Note also that $\dim_{\mathbb{C}} \mathcal{C}(G) = k$, as the characteristic functions $\delta_j$ of the conjugacy classes form a basis, where $\delta_j(g) = 1$ if $g \in \mathcal{C}_j$, and 0 otherwise.

Define Hermitian inner product on $\mathcal{C}(G)$ by

$$\langle f, f' \rangle = \frac{1}{|G|} \sum_{g \in G} \overline{f(g)}f'(g) = \frac{1}{|G|} \sum_{j=1}^k \overline{|\mathcal{C}_j|} \overline{f(g_j)}f'(g_j) = \sum_{j=1}^k \frac{1}{|C_G(g_j)|} \overline{f(g_j)}f'(g_j)$$

using orbit-stabiliser: $|\mathcal{C}(x)| = |G : C_G(x)|$, where $C_G(x)$ is the centraliser of $x$ in $G$.

For characters, $\langle \chi, \chi' \rangle = \frac{1}{|C_G(g_j)|} \overline{\chi(g_j^{-1})} \chi'(g_j)$ is a real symmetric form.

Main result follows.

(5.6) **Big Theorem (Completeness of characters).** The $\mathbb{C}$-irreducible characters of $G$ form an orthonormal basis of the space of class functions of $G$. Moreover,

(a) If $\rho : G \to GL(V)$, $\rho' : G \to GL(V')$ are irreducible representations of $G$ affording characters $\chi$, $\chi'$ then

$$\langle \chi, \chi' \rangle = \begin{cases} 1 & \text{if } \rho, \rho' \text{ are isomorphic} \\ 0 & \text{otherwise} \end{cases}$$

(b) Each class function of $G$ can be expressed as a linear combinations of irreducible characters of $G$.

**Proof.** In chapter 6.

(5.7) **Corollary.** Complex representations of finite groups are characterised by their characters.

**Proof.** Have $\rho : G \to GL(V)$ affording $\chi$. Complete reducibility (3.3) says $\rho = m_1 \rho_1 \oplus \ldots \oplus m_k \rho_k$, where $\rho_j$ is irreducible and $m_j \geq 0$. Then $m_j = \langle \chi, \chi_j \rangle$ where $\chi_j$ is afforded by $\rho_j$, since $\chi = m_1 \chi_1 + \ldots + m_k \chi_k$ and $\langle \chi, \chi_j \rangle = \langle m_1 \chi_1 + \ldots + m_k \chi_k, \chi_j \rangle = m_j$, by (5.6)(a). \hfill \Box

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(5.8) Corollary (Irreducibility criterion). If $\rho$ is a complex representation of $G$ affording $\chi$ then $\rho$ irreducible $\iff \langle \chi, \chi \rangle = 1$.

Proof. ($\Rightarrow$) Orthonormality.

($\Leftarrow$) Assume $\langle \chi, \chi \rangle = 1$. (3.3) says $\chi = \sum m_j \chi_j$, for $\chi_j$ irreducible, $m_j \geq 0$. Then $\sum m_j^2 = 1$, so $\chi = \chi_j$ for some $j$. Therefore $\chi$ is irreducible.

(5.9) Theorem. If the irreducible complex representations of $G$ have dimensions $n_1, \ldots, n_k$, then $|G| = \sum n_i^2$.

(Recall end of chapter 4.)

Proof. Recall from (3.5), $\rho_{\text{reg}} : G \to GL(\mathbb{C}G)$, the regular representation of $G$, of dimension $|G|$. Let $\pi_{\text{reg}}$ be its character.

Claim. $\pi_{\text{reg}}(1) = |G|$ and $\pi_{\text{reg}}(h) = 0$ if $h \neq 1$.

Proof. Easy. Let $G = \{g_1, \ldots, g_n\}$ and take $h \in G, h \neq 1$. For $1 \leq i \leq n$, $hg_i = g_j$, some $j \neq i$, so $i^{th}$ row of $[\rho_{\text{reg}}(h)]_{ij}$ has 0s in every place, except column $j$ – in particular, the $(i, i)^{th}$ entry is 0 for all $i$. Hence $\pi_{\text{reg}}(h) = \text{tr} [\rho_{\text{reg}}(h)]g = 0$.

By claim, $\pi_{\text{reg}} = \sum n_j \chi_j$ with $n_j = \chi_j(1)$:

$$n_j = \langle \pi_{\text{reg}}, \chi_j \rangle = \frac{1}{|G|} \sum_{g \in G} \overline{\pi_{\text{reg}}(g)} \chi_j(g) = \frac{1}{|G|} |G| \chi_j(1) = \chi_j(1)$$

\(\square\)

(5.10) Corollary. The number of irreducible characters of $G$ (up to equivalence) equals $k$, the number of conjugacy classes.

(5.11) Corollary. Elements $g_1, g_2 \in G$ are conjugate iff $\chi(g_1) = \chi(g_2)$ for all irreducible characters of $G$.

Proof. ($\Rightarrow$) Characters are class functions.

($\Leftarrow$) Let $\delta$ be the characteristic function of the class of $g_1$. Then $\delta$ is a class function, so can be written as a linear combination of the irreducible characters of $G$, by (5.6)(b). Hence $\delta(g_2) = \delta(g_1) = 1$. So $g_2 \in \mathcal{C}_G(g_1)$.

\(\square\)

Recall from (5.5) the inner product on $\mathcal{C}(G)$ and the real symmetric form $\langle \cdot, \cdot \rangle$ for characters.

(5.12) Definition. $G$ finite, $F = \mathbb{C}$. The character table of $G$ is the $k \times k$ matrix

$X = [\chi_i(g_j)]$ where $\chi_1(= 1), \chi_2, \ldots, \chi_k$ are the irreducible characters of $G$, and $C_1(= \{1\}), C_2, \ldots, C_k$ are the conjugacy classes, with $g_j \in C_j$.

I.e., the $(i, j)^{th}$ entry of $X$ is $\chi_i(g_j)$.

Examples. $C_2 = \{x : x^2 = 1\}$

$$\begin{array}{c|c}
\chi_1 & x \\
\hline
1 & 1 \\
\chi_2 & 1 & -1
\end{array}$$

$C_3 = \{x : x^3 = 1\}$

$$\begin{array}{c|ccc}
\chi_1 & \chi_2 & \chi_3 \\
\hline
1 & x & x^2 \\
\chi_1 & 1 & 1 & 1 \\
\chi_2 & 1 & \omega & \omega^2 \\
\chi_3 & 1 & \omega^2 & \omega
\end{array}$$

where $\omega = e^{2\pi i/3} \in \mu_3$.  

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\[ G = D_6 = \langle a, b : a^3 = b^2 = 1, bab^{-1} = a^{-1} \rangle \cong S_3. \]

In (2.17) we found a complete set of non-isomorphic irreducible \( CG \)-modules: \( U_1, U_2, U_3 \).

Let \( \chi_i = \chi_{U_i}, \ (1 \leq i \leq 3) \).

\[
\begin{array}{c|ccc}
\chi_1 & \{a, a^2\} & \{b, ab, a^2b\} & \leftarrow g_j \\
1 & 1 & 1 & 1 \\
\chi_2 & 1 & 1 & -1 \\
\chi_3 & 2 & -1 & 0 \\
\end{array}
\]

Orthogonality:

\[
\frac{1 \times 2}{6} + \frac{(-1)(1)}{3} = 0 \quad (\text{rows 2 \\& 3})
\]

\[
\frac{2^2}{6} + \frac{(-1)^2}{3} = 1 \quad (\text{row 3})
\]
6. Proofs and Orthogonality

We want to prove (5.6), the Big Theorem. We’ll do this in two ways.

Proof 1 of (5.6)(a). Fix bases of $V$ and $V'$. Write $R(g)$, $R'(g)$ for the matrices of $\rho(g)$, $\rho'(g)$ with respect to these, respectively.

$$\langle \chi', \chi \rangle = \frac{1}{|G|} \sum_{g \in G} \chi'(g^{-1})\chi(g) = \frac{1}{|G|} \sum_{g \in G} R'(g^{-1})_{ii}R(g)_{jj}$$

Let $\phi : V \to V'$ be linear, and define $\widetilde{\phi} : V \to V'$, $v \mapsto \frac{1}{|G|} \sum_{g \in G} \rho'(g^{-1})\rho(g)(v)$.

Then this ‘average’ $\widetilde{\phi}$ is a $G$-homomorphism. For if $h \in G$,

$$\rho'(h^{-1})\rho(h)(v) = \frac{1}{|G|} \sum_{g \in G} \rho'(gh^{-1})\rho(gh)(v) = \frac{1}{|G|} \sum_{g' \in G} \rho'(g'h^{-1})\rho(g')(v) = \widetilde{\phi}(v).$$

Assume first that $\rho, \rho'$ are not isomorphic. Schur’s Lemma says $\widetilde{\phi} = 0$ for any linear $\phi : V \to V'$.

Let $\phi = \varepsilon_{\alpha\beta}$ have matrix $E_{\alpha\beta}$ (with respect to our basis), namely 0 everywhere except 1 in the $(\alpha, \beta)$th place.

Then $\varepsilon_{\alpha\beta} = 0$, so $\frac{1}{|G|} \sum_{g \in G} (R'(g^{-1})E_{\alpha\beta}R(g))_{ij} = 0$.

Thus $\frac{1}{|G|} \sum_{g \in G} R'(g^{-1})_{ii}R(g)_{jj} = 0$ for all $i, j$.

With $\alpha = i, \beta = j$, $\frac{1}{|G|} \sum_{g \in G} R'(g^{-1})_{ii}R(g)_{jj} = 0$. Sum over $i, j$ and conclude $\langle \chi', \chi \rangle = 0$.

Now assume that $\rho, \rho'$ are isomorphic, so $\chi = \chi'$. Take $V = V'$, $\rho = \rho'$. If $\phi : V \to V$ is linear, then $\widetilde{\phi} \in \text{Hom}_G(V, V)$.

Now $\text{tr} \phi = \text{tr} \widetilde{\phi}$, as $\text{tr} \widetilde{\phi} = \frac{1}{|G|} \sum \text{tr} (\rho(g^{-1})\rho(g)) = \frac{1}{|G|} \sum \text{tr} \phi = \text{tr} \phi$.

By Schur, $\widetilde{\phi} = \lambda \text{id}$ for some $\lambda \in \mathbb{C}$ (depending on $\phi$). Now $\lambda = \frac{1}{n} \text{tr} \phi$.

Let $\phi = \varepsilon_{\alpha\beta}$, so $\text{tr} \phi = \delta_{\alpha\beta}$. Hence $\varepsilon_{\alpha\beta} = \frac{1}{n} \delta_{\alpha\beta} \text{id} = \frac{1}{|G|} \sum_g \rho(g^{-1})\varepsilon_{\alpha\beta}\rho(g)$.

In terms of matrices, take the $(i, j)^{th}$ entry: $\frac{1}{|G|} \sum_g R(g^{-1})_{ii}R(g)_{jj} = \frac{1}{n} \delta_{ij}$.

and put $\alpha = i, \beta = j$ to get $\frac{1}{|G|} \sum_g R(g^{-1})_{ii}R(g)_{jj} = \frac{1}{n} \delta_{ij}$.

Finally sum over $i, j$: $\langle \chi, \chi \rangle = 1$. □
Before proving (b), let’s prove column orthogonality, assuming (5.10).

(6.1) Theorem (column orthogonality). \[ \sum_{i=1}^{k} \chi_i(g_j) \chi_i(g_e) = \delta_{j\ell} |C_G(g_j)|. \]

This has an easy corollary:

(6.2) Corollary. \[ |G| = \sum_{i=1}^{k} \chi_i^2(1). \]

Proof of (6.1). \[ \delta_{ij} = \langle \chi_i, \chi_j \rangle = \sum_{\ell} \frac{1}{|C_G(g_\ell)|} \chi_i(g_\ell) \chi_j(g_\ell). \]

Consider the character table \( X = (\chi_i(g_j)) \).

Then \( XD^{-1}X^t = I_k \times k \), where \( D = (|C_G(g_1)|, \ldots, |C_G(g_k)|) \).

As \( X \) is a square matrix, it follows that \( D^{-1}X^t \) is the inverse of \( X \). So \( X^t X = D \).

Proof of (5.6)(b). List all the irreducible characters \( \chi_1, \ldots, \chi_\ell \) of \( G \). It’s enough to show that the orthogonal complement of \( \text{span}\{\chi_1, \ldots, \chi_\ell\} \) in \( C(G) \) is 0.

To see this, assume \( f \in C(G) \) with \( \langle f, \chi_j \rangle = 0 \) for all irreducible \( \chi_j \).

Let \( \rho : G \to GL(V) \) be irreducible affording \( \chi \in \{\chi_1, \ldots, \chi_\ell\} \). Then \( \langle f, \chi \rangle = 0 \).

Consider \( \frac{1}{|G|} \sum f(g) \rho(g) : V \to V \). This is a \( G \)-homomorphism, so as \( \rho \) is irreducible it must be \( \lambda \text{id} \) for some \( \lambda \in \mathbb{C} \) (by Schur).

Now, \( n\lambda = \text{tr} \left( \frac{1}{|G|} \sum f(g) \rho(g) \right) = \frac{1}{|G|} \sum f(g) \chi(g) = 0 = \langle f, \chi \rangle \).

So \( \lambda = 0 \). Hence \( \sum f(g) \rho(g) = 0 \), the zero endomorphism on \( V \), for all representations \( \rho \). Take \( \rho = \rho_{\text{reg}} \), where \( \rho_{\text{reg}}(g) : e_1 \mapsto e_g \) (\( g \in G \)), the regular representation.

So \( \sum_g f(g) \rho_{\text{reg}}(g) : e_1 \mapsto \sum_g f(g)e_g \). It follows that \( \sum g f(g)e_g = 0 \).

Therefore \( f(g) = 0 \) for all \( g \in G \). And so \( f = 0 \). \( \square \)

Various important corollaries follow from this:

- (5.10) \# irreducibles of \( G \) = \# conjugacy classes
- (6.1) column orthogonality
- (6.2) \( |G| = \sum \chi_i^2(1) = \sum_{i=1}^{k} n_i^2 \)
- (5.11) irreducible \( \chi \) is constant on conjugacy classes – i.e., \( g_1 \sim_G g_2 \Rightarrow \chi(g_1) = \chi(g_2) \).
- \( g, g^{-1} \) are \( G \)-conjugate \( \Leftrightarrow \chi(g) \in \mathbb{R} \) for all irreducible \( \chi \) – as \( \chi(g^{-1}) = \overline{\chi(g)} \).
Example.

| \( \chi_1 \) | 1 | 1 | 1 |
| \( \chi_2 \) | 1 | 1 | -1 |
| \( \chi_3 \) | 2 | -1 | 0 |

\( \mapsto |G_{G}(g_{j})| \)

\( \mapsto g_{j} \)

<table>
<thead>
<tr>
<th>6</th>
<th>3</th>
<th>2 &amp; \leftarrow \text{coming from operations on equilateral triangle}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>a</td>
<td>b</td>
</tr>
</tbody>
</table>

Column orthogonality: \( \sum_{i=1}^{3} \chi_{i}(g_{r}) \chi_{i}(g_{s}) \).

- For \( r = 1, s = 2 \): \( 1.1 + 1.1 + 2(-1) = 0 \), \( r \neq s \)
- For \( r = 1, s = 3 \): \( 1.1 + 1(-1) + 2.0 = 0 \), \( r \neq s \)
- For \( r = 2, s = 2 \): \( 1.1 + 1.1 + (-1)(-1) = 3 \), \( r = s \), weight by \( |C_{G}(g_{r})| \)

** Non-examinable section **

Proof 2 of (5.6)(a). (Uses starred material at the end of chapter 4.)

\( X \) irreducible \( G \)-space, \( V \) any \( G \)-space. \( V = \bigoplus_{i=1}^{m} U_{i} \), with \( U_{i} \) irreducible.

Then the number of \( U_{j} \) isomorphic to \( X \) is independent of the decomposition. We wrote \( (V : X) \) for this number, and in (4.7) we saw \( (V : X) = \dim_{C} \text{Hom}_{G}(V,X) \ (\ast) \).

Let \( \rho : G \rightarrow GL(U) \) have character \( \chi \) Write \( U^{G} = \{ u \in U : \rho(g)u = u \forall g \in G \} \), the \( G \)-invariants of \( U \).

Consider the map \( \pi : U \rightarrow U, u \mapsto \frac{1}{|G|} \sum_{g} \rho(g)u \).

This is a projection onto \( U^{G} \) (because it’s a \( G \)-homomorphism, and when restricted to \( U^{G} \) it acts as the identity there). Verify \( \dim U^{G} = tr \pi = \frac{1}{|G|} \sum_{g} \chi_{U}(g) \ (\ast \ast) \) (by decomposing \( U \) and looking at bases).

Now choose \( U = \text{Hom}_{C}(V,V') \) with \( V,V' \) being \( G \)-spaces. \( G \) acts on \( U \) via \( g.\theta(v) = \rho_{V}(g)(\theta\rho_{V'}(g^{-1})v) \) for \( \theta \in U \).

But \( \text{Hom}_{G}(V,V') = (\text{Hom}_{C}(V,V'))^{G} \), so by \( (\ast \ast) \), \( \dim \text{Hom}_{G}(V,V') = \frac{1}{|G|} \sum_{g} \chi_{U}(g) \).

Finally, show \( \chi_{U}(g) = \chi_{V'}(g^{-1})\chi_{V}(g) \) – see section on tensor products in chapter 9.

The orthogonality of the irreducible characters now follows from \( (\ast) \).

\( \Box \)

** End of non-examinable section **
7. Permutation Representations

Preview was given in (3.7). Recall:

- \( G \) finite, acting on finite set \( X = \{x_1, \ldots, x_n\} \).
- \( \mathbb{C}X = \mathbb{C}\)-space, basis \( \{e_{x_1}, \ldots, e_{x_n}\} \) of dimension \( |X| \). \( \mathbb{C}X = \{ \sum_j a_je_{x_j} : a_j \in \mathbb{C} \} \).
- corresponding permutation representation, \( \rho_X : G \to GL(\mathbb{C}X) \), \( g \mapsto \rho(g) \), where \( \rho(g) : e_{x_j} \mapsto e_{gx_j} \), extended linearly. So \( \rho_X(g) : \sum x \in X a_xe_x \mapsto \sum x \in X g_xa_xe_{gx} \).
- \( \rho_X \) is the permutation representation corresponding to the action of \( G \) on \( X \).
- matrices representing \( \rho_X(g) \) with respect to the basis \( \{e_x\}_{x \in X} \) are permutation matrices: 0 everywhere except one 1 in each row and column, and \( (\rho(g))_{ij} = 1 \) precisely when \( gx_j = x_i \).

(7.1) Permutation character \( \pi_X \) is \( \pi_X(g) = |\text{fix}_X(g)| = |\{x \in X : gx = x\}| \).

(7.2) \( \pi_X \) always contains 1G. For: \( \text{span}(e_{x_1} + \ldots + e_{x_n}) \) is a trivial \( \mathbb{G} \)-subspace of \( \mathbb{C}X \) with \( \mathbb{G} \)-invariant complement \( \text{span}(\sum a_xe_x : \sum a_x = 0) \).

(7.3) ‘Burnside’s Lemma’ (Cauchy, Frobenius). \( \langle \pi_X, 1 \rangle = \# \text{ orbits of } G \text{ on } X \).

Proof. If \( X = X_1 \cup \ldots \cup X_\ell \), a disjoint union of orbits, then \( \pi_X = \pi_{X_1} + \ldots + \pi_{X_\ell} \) with \( \pi_{X_j} \) the permutation character of \( G \) on \( X_j \). So to prove the claim, it’s enough to show that if \( G \) is transitive on \( X \) then \( \langle \pi_X, 1 \rangle = 1 \).

So, assume \( G \) is transitive on \( X \). Then

\[
\langle \pi_X, 1 \rangle = \frac{1}{|G|} \sum_{g \in G} \pi_X(g) = \frac{1}{|G|} \left| \{(g,x) \in G \times X : gx = x\} \right| = \frac{1}{|G|} \sum_{x \in X} |G_x| = \frac{1}{|G|} |X| |G_x| = \frac{1}{|G|} |G| = 1 \quad \square
\]

(7.4) Lemma. Let \( G \) act on sets \( X_1, X_2 \). Then \( G \) acts on \( X_1 \times X_2 \) via \( g(x_1, x_2) = (gx_1, gx_2) \). The character \( \pi_{X_1 \times X_2} = \pi_{X_1} \pi_{X_2} \) and so \( \langle \pi_{X_1}, \pi_{X_2} \rangle = \# \text{ orbits of } G \text{ on } X_1 \times X_2 \).

Proof. \( \langle \pi_{X_1}, \pi_{X_2} \rangle = \langle \pi_{X_1}, \pi_{X_2}, 1 \rangle = \langle \pi_{X_1 \times X_2}, 1 \rangle = \# \text{ orbits of } G \text{ on } X_1 \times X_2 \) (by (7.3)). \( \square \)

(7.5) Let \( G \) act on \( X \), \( |X| > 2 \). Then \( G \) is 2-transitive on \( X \) if \( G \) has just two orbits on \( X \times X \), namely \( \{(x,x) : x \in X\} \) and \( \{(x_1,x_2) : x_i \in X, x_1 \neq x_2\} \).

(7.6) Lemma. Let \( G \) act on \( X \), \( |X| > 2 \). Then \( \pi_X = 1 + \chi \) with \( \chi \) irreducible \( \iff \) \( G \) is 2-transitive on \( X \).

Proof. \( \pi_X = m_1 + m_2\chi_2 + \ldots + m_\ell\chi_\ell \) with \( 1, \chi_2, \ldots, \chi_\ell \) distinct irreducibles and \( m_i \in \mathbb{Z}_{\geq 0} \). Then \( \langle \pi_X, \pi_X \rangle = \sum_{i=1}^{\ell} m_i^2 \). Hence \( G \) is 2-transitive on \( X \) iff \( \ell = 2, m_1 = m_2 = 1 \). \( \square \)

(7.7) \( S_n \) acting on \( X_n \) (see 1.6) is 2-transitive. Hence \( \pi_{X_n} = 1 + \chi \) with \( \chi \) irreducible of degree \( n - 1 \). Similarly for \( A_n \) (\( n > 3 \))
(7.8) Example. $G = S_4$.

Conjugacy classes correspond to different cycle types.

<table>
<thead>
<tr>
<th>Cycle Type</th>
<th>1</th>
<th>3 (12)(34)</th>
<th>8 (123)</th>
<th>6 (1234)</th>
<th>6 (12)</th>
</tr>
</thead>
<tbody>
<tr>
<td>trivial</td>
<td>$\chi_1$</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>sign</td>
<td>$\chi_2$</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>-1</td>
</tr>
<tr>
<td>$\pi_{X_4} - 1$</td>
<td>$\chi_3$</td>
<td>3</td>
<td>-1</td>
<td>0</td>
<td>-1</td>
</tr>
<tr>
<td>$\chi_3 \times \chi_2$</td>
<td>$\chi_4$</td>
<td>3</td>
<td>-1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>$\chi_5$</td>
<td>$\chi_5$</td>
<td>$d$</td>
<td>$x$</td>
<td>$y$</td>
<td>$z$</td>
</tr>
</tbody>
</table>

two linear characters
since $S_4/S'_4 = C_2$

$\langle \chi_{reg} - \chi_1 - \chi_2 - 3\chi_3 - 3\chi_4 \rangle = 2$.

For $\chi_7$, first $\sum d_i^2 = 120$ gives $\deg \chi_7 = 6$, and orthogonality for the remaining entries.

$\langle \chi_{\binom{5}{2}}, \chi_{\binom{5}{2}} \rangle = 3$
$\langle \chi_{\binom{5}{2}}, 1 \rangle = 1$
$\langle \chi_{\binom{5}{2}}, \chi_3 \rangle = 1$

$\Rightarrow \chi_{\binom{5}{2}} = 1 + \chi_3 + \psi$

$\psi$ has degree 5 (and is actually $\chi_6$ in the table).

See chapter 10 for the method of induced characters, and chapter 9 for symmetric and alternating powers.

(7.9) Example. $G = S_5$.

<table>
<thead>
<tr>
<th>Cycle Type</th>
<th>1</th>
<th>15</th>
<th>20</th>
<th>24</th>
<th>10</th>
<th>20</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>trivial</td>
<td>$\chi_1$</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>sign</td>
<td>$\chi_2$</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>$\pi_{X_5} - 1$</td>
<td>$\chi_3$</td>
<td>4</td>
<td>0</td>
<td>1</td>
<td>-1</td>
<td>2</td>
<td>-1</td>
</tr>
<tr>
<td>$\chi_3 \times \chi_2$</td>
<td>$\chi_4$</td>
<td>4</td>
<td>0</td>
<td>1</td>
<td>-1</td>
<td>-2</td>
<td>1</td>
</tr>
<tr>
<td>$\chi_5$</td>
<td>$\chi_5$</td>
<td>5</td>
<td>1</td>
<td>-1</td>
<td>0</td>
<td>-1</td>
<td>1</td>
</tr>
<tr>
<td>$\chi_5 \times \chi_2$</td>
<td>$\chi_6$</td>
<td>5</td>
<td>1</td>
<td>-1</td>
<td>0</td>
<td>1</td>
<td>-1</td>
</tr>
<tr>
<td>$\chi_7$</td>
<td>$\chi_7$</td>
<td>6</td>
<td>-2</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

There are various methods to get $\chi_5, \chi_6$ of degree 5.

One way is to note that if $X = \text{Syl}_5(G)$ then $|X| = 6$ and one checks that $\langle \chi_X, \chi_X \rangle = 2$. Therefore $\pi_X - 1$ is irreducible.

For $\chi_7$, first $\sum d_i^2 = 120$ gives $\deg \chi_7 = 6$, and orthogonality for the remaining entries.

$\langle \chi_{\binom{5}{2}}, \chi_{\binom{5}{2}} \rangle = 3$
$\langle \chi_{\binom{5}{2}}, 1 \rangle = 1$
$\langle \chi_{\binom{5}{2}}, \chi_3 \rangle = 1$

$\Rightarrow \chi_{\binom{5}{2}} = 1 + \chi_3 + \psi$

$\psi$ has degree 5 (and is actually $\chi_6$ in the table).
Let $g \in A_n$. Then \[ |C_{A_n}(g)| = |S_n : C_{S_n}(g)| \uparrow A_n \text{ index } 2 \text{ in } S_n \]
\[ |C_{A_n}(g)| = |A_n : C_{A_n}(g)| \]

but not necessarily equal: e.g., if $\sigma = (123)$, then $C_{A_n}(\sigma) = \{\sigma\}$, but $C_{S_n}(\sigma) = \{\sigma, \sigma^{-1}\}$.

We know $|S_n : A_n| = 2$, and in fact:

(7.11) If $g \in A_n$ then $C_{S_n}(g) = C_{A_n}(g)$ precisely when $g$ commutes with some odd permutation; otherwise it breaks up into two classes of equal size. (In the latter case, precisely when the disjoint cycle decomposition of $g$ is a product of odd cycles of distinct lengths.)

Proof. See James & Liebeck 12.17.

(7.12) $G = A_4$. Write $\omega = e^{2\pi i/3}$.

\[
\begin{array}{cccccccc}
1_G & \chi_1 & \chi_2 & \chi_3 & \chi_4 \\
1 & 1 & 3 & 1 & 1 \\
(12)(34) & (123) & -1 & 0 & 0 \\
(123)^{-1} & 1 & -1 & \omega & \omega^2 \\
\end{array}
\]

\[
\sum d_i^2 = 1^2 + 3^2 + \omega^2 + \omega^2 = 6
\]

Final two linear characters are found via $G/G' = G/V_4 = C_3$, by lifting – see chapter 8.

For $A_5$ see Telemann chapter 11, or James & Liebeck 20.13.
8. Normal Subgroups and Lifting Characters

(8.1) Lemma. Let $N \triangleleft G$, let $\tilde{\rho} : G/N \to GL(V)$ be a representation of $G/N$. Then
\[ \rho : G \to GL(V) \] is a representation of $G$, where $\rho(g) = \tilde{\rho}(gN)$ (and $q$ is the natural homomorphism). Moreover, $\rho$ is irreducible if $\tilde{\rho}$ is.

The corresponding characters satisfy $\chi(g) = \tilde{\chi}(gN)$ for $g \in G$, and $\deg \chi = \deg \tilde{\chi}$. We say that $\tilde{\chi}$ lifts to $\chi$.

The lifting sending $\tilde{\chi} \mapsto \chi$ is a bijection between
\[ \text{irreducibles of } G/N \longleftrightarrow \text{irreducibles of } G \text{ with } N \text{ in the kernel} \]

Proof. (See examples sheet 1, question 4.)

Note: $\chi(g) = \text{tr} (\rho(g)) = \text{tr} (\tilde{\rho}(gN)) = \tilde{\chi}(gN) \forall g$, and $\chi(1) = \tilde{\chi}(N)$, so $\deg \chi = \deg \tilde{\chi}$.

Bijection. If $\tilde{\chi}$ is a character of $G/N$ and $\chi$ is a lift to $G$ then $\tilde{\chi}(N) = \chi(1)$. Also, if $k \in N$ then $\chi(k) = \tilde{\chi}(kN) = \tilde{\chi}(N) = \chi(1)$. So $N \leq \ker \chi$.

Now let $\chi$ be a character of $G$ with $N \leq \ker \chi$. Suppose $\rho : G \to GL(V)$ affords $\chi$.

Define $\tilde{\rho} : G/N \to GL(V)$, $gN \mapsto \rho(g)$ for $g \in G$. This is well-defined (as $N \leq \ker \chi$) and $\tilde{\rho}$ is a homomorphism, hence a representation of $G/N$. If $\tilde{\chi}$ is the character of $\tilde{\rho}$ then $\tilde{\chi}(gN) = \chi(g)$ for all $g \in G$.

Finally, check irreducibility is preserved. \qed

Definition. The derived subgroup of $G$ is $G' = \langle [a, b] : a, b \in G \rangle$, where $[a, b] = aba^{-1}b^{-1}$ is the commutator of $a$ and $b$. ($G'$ is a crude measure of how abelian $G$ is.)

(8.2) Lemma. $G'$ is the unique minimal normal subgroup of $G$ such that $G/G'$ is abelian.

(i.e., $G/N$ abelian $\Rightarrow G' \subseteq N$, and $G/G'$ is abelian.)

$G$ has precisely $\ell = |G/G'|$ representations of degree 1, all with kernel containing $G'$ and obtained by lifting from $G/G'$.

Proof. $G' \triangleleft G$ — easy exercise.

Let $N \triangleleft G$. Let $g, h \in G$. Then $g^{-1}h^{-1}gh \in N \iff ghN = hqN \iff (gN)(hN) = (hN)(gN)$. So $G' \subseteq N \iff G/N$ abelian. Since $G' \triangleleft G$, $G/G'$ is an abelian group.

By (4.5), $G/G'$ has exactly $\ell$ irreducible characters, $\chi_1, \ldots, \chi_\ell$, all of degree 1. The lifts of these to $G$ also have degree 1 and by (8.1) these are precisely the irreducible characters $\chi_i$ of $G$ such that $G' \leq \ker \chi_i$.

But any linear character $\chi$ of $G$ is a homomorphism $\chi : G \to \mathbb{C}^\times$, hence $\chi(ghg^{-1}h^{-1}) = \chi(g)\chi(h)\chi(g^{-1})\chi(h^{-1}) = 1$.

Therefore $G' \leq \ker \chi$, and so $\chi_1, \ldots, \chi_\ell$ are all irreducible characters of $G$. \qed

Examples. (i) Let $G = S_n$. Show $G' = A_n$. Thus $G/G' \cong C_2$.

So $S_n$ must have exactly two linear characters.
(ii) \( G = A_4 \).

<table>
<thead>
<tr>
<th></th>
<th>((12)(34))</th>
<th>((123))</th>
<th>((123)^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1_G)</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>(\chi_2)</td>
<td>1</td>
<td>1</td>
<td>(\omega)</td>
</tr>
<tr>
<td>(\chi_3)</td>
<td>1</td>
<td>(\omega^2)</td>
<td>(\omega)</td>
</tr>
<tr>
<td>(\chi_4)</td>
<td>3</td>
<td>-1</td>
<td>0</td>
</tr>
</tbody>
</table>

Let \( N = \{1, (12)(34), (13)(24), (14)(23)\} \leq G \). In fact, \( N \cong V_4, N \vartriangleleft G, \) and \( G/N \cong C_3 \).

Also, \( G' = V_4 \), so \( G/G' \cong C_3 \).

**Lemma.** \( G \) is **not** simple iff \( \chi(g) = \chi(1) \) for some irreducible character \( \chi \neq 1_G \) and \( 1 \neq g \in G \). Any normal subgroup of \( G \) is the intersection of kernels of some of the irreducibles of \( G \), \( N = \bigcap_{\chi_{i, \text{irred}}} \ker \chi_i \).

**Proof.** If \( \chi(g) = \chi(1) \) for some non-principal character \( \chi \) (afforded by \( \rho \), say), then \( g \in \ker \rho \) (by (5.3)). Therefore if \( g \neq 1 \) then \( 1 \neq \ker \rho < G \).

If \( 1 \neq N < G \), take an irreducible \( \tilde{\chi} \) of \( G/N \) (\( \tilde{\chi} \neq 1_{G/N} \)). Lift to get an irreducible \( \chi \) afforded by \( \rho \) of \( G \), then \( N \leq \ker \rho < G \). Therefore \( \chi(g) = \chi(1) \) for \( g \in N \).

In fact, if \( 1 \neq N < G \) then \( N \) is the intersection of the kernels of the lifts of all of the irreducibles of \( G/N \). \( \leq \) is clear. For \( \geq \): if \( g \in G \setminus N \) then \( gN \neq N \), so \( \tilde{\chi}(gN) \neq \tilde{\chi}(N) \) for some irreducible \( \tilde{\chi} \) of \( G/N \), and then lifting \( \tilde{\chi} \) to \( X \) we have \( \chi(g) \neq \chi(1) \). \( \square \)
9. Dual Spaces and Tensor Products of Representations

Recall (5.5), (5.6): \( \mathcal{C}(G) = \mathbb{C}\)-space of class functions of \( G \), \( \dim_{\mathbb{C}} \mathcal{C}(G) = k \), with basis \( \chi_1, \ldots, \chi_k \), the irreducible characters of \( G \).

- \((f_1 + f_2)(g) = f_1(g) + f_2(g)\)
- \((f_1f_2)(g) = f_1(g)f_2(g)\)
- \(\exists \) involution (homomorphism of order 2) \( f \mapsto f^* \) where \( f^*(g) = f(g^{-1}) \)
- \(\exists \) inner product \( (.,.)\)

Duality

(9.1) Lemma. Let \( \rho : G \to GL(V) \) be a representation over \( F \) and let \( V^* = \text{Hom}_F(V, F) \), the dual space of \( V \).

Then \( V^* \) is a \( G \)-space under \( \rho^*(g)\phi(v) = \phi(\rho(g^{-1})v) \), the dual representation of \( \rho \).

Its character is \( \chi_{\rho^*}(g) = \chi_{\rho}(g^{-1}) \).

Proof. \( \rho^*(g_1)(\rho^*(g_2)\phi)(v) = (\rho^*(g_2)\phi)(\rho(g_1^{-1})v) = \phi(\rho(g_2^{-1})\rho(g_1^{-1})v) \)

\[ = \phi(\rho(g_1g_2)^{-1}(v)) = (\rho^*(g_1g_2)\phi)(v) \]

Character. Fix \( g \in G \) and let \( e_1, \ldots, e_n \) be a basis of \( V \) of eigenvectors of \( \rho(g) \), say \( \rho(g)e_j = \lambda_j e_j \). Let \( \varepsilon_1, \ldots, \varepsilon_n \) be the dual basis.

Then \( \rho^*(g)\varepsilon_j = \lambda_j^{-1}\varepsilon_j \), for \( (\rho^*(g)\varepsilon_j)(e_i) = \varepsilon_j(\rho(g^{-1})e_i) = \varepsilon_j\lambda_j^{-1}e_i = \lambda_j^{-1}\varepsilon_j e_i \) for all \( i \).

Hence \( \chi_{\rho^*}(g) = \sum \lambda_j^{-1} = \chi_{\rho}(g^{-1}) \). \( \square \)

(9.2) Definition. \( \rho : G \to GL(V) \) is self-dual if \( V \cong V^* \) (as an isomorphism of \( G \)-spaces). Over \( F = \mathbb{C} \), this holds iff \( \chi_{\rho}(g) = \chi_{\rho}(g^{-1}) \), and since this \( = \chi_{\rho}(g) \), it holds iff \( \chi_{\rho}(g) \in \mathbb{R} \) for all \( g \).

Example. All irreducible representations of \( S_n \) are self-dual: the conjugacy classes are determined by cycle types, so \( g, g^{-1} \) are always \( S_n \)-conjugate. Not always true for \( A_n \): it’s okay for \( A_5 \), but not for \( A_7 \) – see sheet 2, question 8.

Tensor Products

\( V \) and \( W \), \( F \)-spaces, \( \dim V = m, \dim W = n \). Fix bases \( v_1, \ldots, v_m \) and \( w_1, \ldots, w_n \) of \( V, W \), respectively. The tensor product space \( V \otimes W \) (or \( V \otimes_F W \)) is an \( mn \)-dimensional \( F \)-space with basis \( \{ v_i \otimes w_j : 1 \leq i \leq m, 1 \leq j \leq n \} \). Thus:

(a) \( V \otimes W = \left\{ \sum_{1 \leq i \leq m} \sum_{1 \leq j \leq n} \lambda_{ij} v_i \otimes w_j : \lambda_{ij} \in F \right\} \), with ‘obvious’ addition and scalar multiplication.

(b) if \( v = \sum \alpha_i v_i \in V \), \( w = \sum \beta_j w_j \in W \), define \( v \otimes w = \sum_{i,j} \alpha_i \beta_j (v_i \otimes w_j) \).

Note: not all elements of \( V \otimes W \) are of this form. Some are combinations, e.g. \( v_1 \otimes w_1 + v_2 \otimes w_2 \), which cannot be further simplified.
(9.3) Lemma. (i) For \( v \in V, w \in W, \lambda \in F \), have \((\lambda v) \otimes w = \lambda (v \otimes w) = v \otimes (\lambda w)\).

(ii) If \( x, x_1, x_2 \in V \) and \( y, y_1, y_2 \in W \), then \((x_1 + x_2) \otimes y = (x_1 \otimes y) + (x_2 \otimes y)\) and \( x \otimes (y_1 + y_2) = (x \otimes y_1) + (x \otimes y_2)\).

Hence \( V \times W \to V \otimes W \), \((v, w) \mapsto v \otimes w\) is bilinear.

Proof. (i) \( v = \sum \alpha_i v_i, w = \sum \beta_j w_j \), then \((\lambda v) \otimes w = \sum_{i,j} (\lambda \alpha_i) \beta_j v_i \otimes w_j\), and \(v \otimes (\lambda w) = \sum_{i,j} \alpha_i (\lambda \beta_j) v_i \otimes w_j\).

All three are equal. (ii) is similar. \(\Box\)

(9.4) Lemma. If \(\{e_1, \ldots, e_m\}\) is a basis of \(V\) and \(\{f_1, \ldots, f_n\}\) is a basis of \(W\), then \(\{e_i \otimes f_j\} : 1 \leq i \leq m, 1 \leq j \leq n\) is a basis of \(V \otimes W\).

Proof. Writing \(v_k = \sum \alpha_{ik} e_i\), \(w_r = \sum \beta_{jr} f_j\), we have \(v_k \otimes w_r = \sum_{i,j} \alpha_{ik} \beta_{jr} (e_i \otimes f_j)\), hence \(\{e_i \otimes f_j\}\) spans \(V \otimes W\), and since there are \(mn\) of them, they are a basis. \(\Box\)

(9.5) Digression. (Tensor products of endomorphisms.) If \(\alpha : V \to V, \beta : W \to W\) are linear endomorphisms, define \(\alpha \otimes \beta : V \otimes W \to V \otimes W\), \(v \otimes w \mapsto \alpha(v) \otimes \beta(w)\), and extend linearly on a basis.

Example. Given bases \(A = \{e_1, \ldots, e_m\}\) of \(V\), and \(B = \{f_1, \ldots, f_n\}\) of \(W\), if \([\alpha]_A = A\) and \([\beta]_B = B\), then ordering the basis \(A \otimes B\) lexicographically (i.e., \(e_1 \otimes f_1, e_1 \otimes f_2, \ldots, e_1 \otimes f_n, e_2 \otimes f_1, \ldots, e_m \otimes f_n\)), we have
\[
[\alpha \otimes \beta]_{A \otimes B} = \begin{bmatrix}
[a_{11} B] & [a_{12} B] & \cdots \\
[a_{21} B] & [a_{22} B] & \cdots \\
\vdots & \vdots & \ddots
\end{bmatrix}
\]

(9.6) Proposition. Let \(\rho : G \to GL(V), \rho' : G \to GL(V')\) be representations of \(G\). Define \(\rho \otimes \rho' : G \to GL(V \otimes V')\) by
\[
(\rho \otimes \rho')(g) : \sum \lambda_{ij} v_i \otimes w_j \mapsto \sum \lambda_{ij} \rho(g)v_i \otimes \rho'(g)w_j
\]

Then \(\rho \otimes \rho'\) is a representation of \(G\), with character \(\chi_{\rho \otimes \rho'}(g) = \chi_\rho(g) \chi_{\rho'}(g)\) for all \(g \in G\).

Hence the product of two characters of \(G\) is also a character of \(G\). Note: example sheet 2, question 2, says that if \(\rho\) is irreducible and \(\rho'\) is degree 1, then \(\rho \otimes \rho'\) is irreducible. If \(\rho'\) is not of degree 1, then this is usually false, since \(\rho \otimes \rho'\) is usually reducible.

Proof. It’s clear that \((\rho \otimes \rho')(g) \in GL(V \otimes V')\) for all \(g\), and so \(\rho \otimes \rho'\) is a homomorphism \(G \to GL(V \otimes V')\).

Let \(g \in G\). Let \(v_1, \ldots, v_m\) be a basis of \(V\) of eigenvectors of \(\rho(g)\), and \(w_1, \ldots, w_n\) be a basis of \(V'\) of eigenvectors of \(\rho'(g)\). So \(\rho(g)v_j = \lambda_j v_j, \rho'(g)w_j = \mu_j w_j\).

Then \((\rho \otimes \rho')(g)(v_i \otimes w_j) = \rho(g)v_i \otimes \rho'(g)w_j = \lambda_i v_i \otimes \mu_j w_j = (\lambda_i \mu_j)(v_i \otimes w_j)\).

So \(\chi_{\rho \otimes \rho'}(g) = \sum_{i,j} \lambda_i \mu_j = \sum_{i=1}^m \lambda_i \sum_{j=1}^n \mu_j = \chi_\rho(g) \chi_{\rho'}(g)\). \(\Box\)

Take \(V = V'\) and define \(V \otimes V = V \otimes V\). Let \(\tau : \sum \lambda_{ij} v_i \otimes v_j \mapsto \sum \lambda_{ij} v_j \otimes v_i\), a linear \(G\)-endomorphism of \(V \otimes V\) such that \(\tau^2 = 1\). Therefore, eigenvalues are \(\pm 1\).
(9.7) Definition. The symmetric square of \( V \) is \( S^2V = \{ x \in V \otimes V : \tau(x) = x \} \).

The exterior square of \( V \) is \( \Lambda^2V = \{ x \in V \otimes V : \tau(x) = -x \} \). (Also called the anti-symmetric square, or wedge.)

(9.8) Lemma. \( S^2V \) and \( \Lambda^2V \) are \( G \)-subspaces of \( V \otimes V \), and \( V \otimes V = S^2V \oplus \Lambda^2V \).

\( S^2V \) has a basis \( \{ v_i v_j := v_i \otimes v_j + v_j \otimes v_i, 1 \leq i \leq j \leq n \} \), so \( \dim S^2V = \frac{1}{2}n(n + 1) \).

\( \Lambda^2V \) has a basis \( \{ v_i \wedge v_j := v_i \otimes v_j - v_j \otimes v_i, 1 \leq i < j \leq n \} \), so \( \dim \Lambda^2V = \frac{1}{2}n(n - 1) \).

**Proof.** Elementary linear algebra.

To show \( V \otimes V \) is reducible, write \( x \in V \otimes V \) as \( x = \frac{1}{2}(x + \tau(x)) + \frac{1}{2}(x - \tau(x)) \). \( \square \)

(9.9) Lemma. If \( \rho : G \to GL(V) \) is a representation affording character \( \chi \), then \( \chi^2 = \chi_S + \chi_\Lambda \) where \( \chi_S (= S^2\chi) \) is the character of \( G \) on the subrepresentation on \( S^2V \), and \( \chi_\Lambda (= \Lambda^2\chi) \) is the character of \( G \) on the subrepresentation on \( \Lambda^2V \).

Moreover, for \( g \in G \), \( \chi_S(g) = \frac{1}{2}(\chi^2(g) + \chi(g^2)) \) and \( \chi_\Lambda(g) = \frac{1}{2}(\chi^2(g) - \chi(g^2)) \).

**Proof.** Compute characters \( \chi_S, \chi_\Lambda \). Fix \( g \in G \). Let \( v_1, \ldots, v_m \) be a basis of \( V \) of eigenvectors of \( \rho(g) \), say \( \rho(g)v_i = \lambda_i v_i \). Then \( g v_i v_j = \lambda_i \lambda_j v_i v_j \) and \( g v_i \wedge v_j = \lambda_i \lambda_j v_i \wedge v_j \).

Hence \( \chi_S(g) = \sum_{1 \leq i < j \leq n} \lambda_i \lambda_j \) and \( \chi_\Lambda(g) = \sum_{1 \leq i < j \leq n} \lambda_i \lambda_j \).

Now \( (\chi(g))^2 = \left( \sum \lambda_i \right)^2 = \sum \lambda_i^2 + 2 \sum_{i < j} \lambda_i \lambda_j = \chi(g^2) + 2 \chi_\Lambda(g) \).

So, \( \chi_\Lambda(g) = \frac{1}{2}(\chi^2(g) - \chi(g^2)) \), and so \( \chi_S(g) = \frac{1}{2}(\chi^2(g) + \chi(g^2)) \), as \( \chi^2 = \chi_S + \chi_\Lambda \). \( \square \)

‘Usual trick to find characters: diagonalise and hope for the best!’

**Example.** \( G = S_5 \) (again)

\[
\begin{array}{cccccccccc}
1 & 15 & 20 & 24 & 10 & 20 & 30 & \leftarrow |C_j| & \leftarrow |g| \\
1_G & \chi_1 & 1 & 1 & 1 & 1 & 1 & 1 \\
\text{sign} & \chi_2 & 1 & 1 & 1 & 1 & -1 & -1 & -1 \\
\pi_{X_5} - 1 & \chi_3 & 4 & 0 & 1 & -1 & 2 & -1 & 0 \\
\chi_3 \chi_2 & \chi_4 & 4 & 0 & 1 & -1 & -2 & 1 & 0 \\
S^2\chi - 1 - \chi_3 & \chi_5 & 5 & 1 & -1 & 0 & -1 & -1 & 1 \\
\chi_5 \chi_2 & \chi_6 & 5 & 1 & -1 & 0 & 1 & 1 & -1 \\
\Lambda^2\chi & \chi_7 & 6 & -2 & 0 & 1 & 0 & 0 & 0 \\
\end{array}
\]

To find \( \chi_5 \) and \( \chi_7 \), we use (9.9) on \( \chi_4 = \chi \).

\[
\begin{array}{cccccccccccc}
\chi^2(g) & 16 & 0 & 1 & 1 & 4 & 1 & 0 \\
\chi(g^2) & 4 & 4 & 1 & -1 & 4 & 1 & 0 \\
\chi_S(g) & 10 & 2 & 1 & 0 & 4 & 1 & 0 \\
\chi_\Lambda(g) & 6 & -2 & 0 & 1 & 0 & 0 & 0 \\
\end{array}
\]

We have seen \( \chi_S \) already as \( \pi_{(5)} \). Check inner product = 3; contains 1, \( \chi_3 \).
Characters of \( G \times H \) (cf. (4.5) for abelian groups)

(9.10) Proposition. If \( G, H \) are finite groups, with irreducible characters \( \chi_1, \ldots, \chi_k \) and \( \psi_1, \ldots, \psi_\ell \) respectively, then the irreducible characters of the direct product \( G \times H \) are precisely \( \{ \chi_i \psi_j : 1 \leq i \leq k, 1 \leq j \leq \ell \} \) where \( \chi_i \psi_j(g, h) = \chi_i(g) \psi_j(h) \).

Proof. If \( \rho : G \to GL(V) \) affording \( \chi \) and \( \rho' : H \to GL(W) \) affording \( \psi \), then \( \rho \otimes \rho' : G \times H \to GL(V \otimes W) \), \( (g, h) \mapsto \rho(g) \otimes \rho'(h) \) is a representation of \( G \times H \) on \( V \otimes W \) by (9.6). And \( \chi \rho \otimes \rho' = \chi \psi \), also by (9.6).

Claim: \( \chi_i \psi_j \) are distinct and irreducible, for:

\[
\langle \chi_i \psi_j, \chi_r \psi_s \rangle_{G \times H} = 1 / |G \times H| \sum_{(g, h)} \chi_i(g) \psi_s(h) \chi_r(g) \psi_j(h) = \delta_{ir} \delta_{js}
\]

Complete set: \( \sum_{i,j} \chi_i \psi_j(1)^2 = \sum_i \chi_i^2(1) \sum_j \psi_j^2(1) = |G| |H| = |G \times H| \).

Exercise. \( D_6 \times D_6 \) has 9 characters.

Digression: a general approach to tensor products

\( V, W, F \)-spaces (general \( F \), even a non-commutative ring).

(9.11) Definition. \( V \otimes W \) is the \( F \)-space with a bilinear map \( t : V \times W \to T, (v, w) \mapsto v \otimes w =: t(v, w) \), such that any bilinear \( f : V \times W \to X \) (\( X \) any \( F \)-space) can be ‘factored through’ it:

\[
V \times W \overset{t}{\longrightarrow} T \quad f \\ \begin{array}{c} \nearrow \ \exists f' \\ \downarrow \ X \end{array}
\]

I.e., there exists linear \( f' : T \to X \) such that \( f' \circ t = f \).

This is the universal property of the tensor product.

Claim. Such \( T \) exists and is unique up to isomorphism.

Existence. Take (huge) space \( M \) with basis \( \{ (v, w) : v \in V, w \in W \} \). Factor out the subspace \( N \) generated by ‘all the things you want to be zero’, i.e. by

\[
\begin{align*}
&(v_1 + v_2, w) - (v_1, w) - (v_2, w) \\
&(v, w_1 + w_2) - (v, w_1) - (v, w_2) \\
&(\lambda v, w) - \lambda(v, w), \quad (v, \lambda w) - \lambda(v, w)
\end{align*}
\]

for all \( v, v_1, v_2 \in V, w, w_1, w_2 \in W, \lambda \in F \).

Define \( t \) to be the map embedding \( V \times W \to M \) followed by the natural quotient map

\[
V \times W \overset{t}{\longrightarrow} M/N \\ \begin{array}{c} \nearrow \ \exists f' \\ \downarrow \ X \end{array}
\]
Lemma. If $s$ satisfying $V$ Uniqueness. Henceforth, we think of $V$ H
Proof. There is a ‘natural’ (basis independent) isomorphism in each of the fo
Lemma. Check $t$ is bilinear (we’ve quotiented out the relevant properties to make it so). $f'$ is defined on our basis of $M$, $(v, w) \mapsto f(v, w)$, extended linearly. $f' = 0$ on all elements of $N$, hence well-defined on $M/N$.

Uniqueness. $V \times W \to T$ Apply universal property with respect to $T, T'$.

Henceforth, we think of $V \otimes W$ as being generated by elements $v \otimes w (v \in V, w \in W)$ and satisfying

$$\begin{aligned}
(v_1 + v_2) \otimes w &= v_1 \otimes w + v_2 \otimes w \\
v \otimes (w_1 + w_2) &= v \otimes w_1 + v \otimes w_2 \\
\lambda(v \otimes w) &= \lambda v \otimes w = v \otimes \lambda w
\end{aligned}$$

(9.12) Lemma. If $e_1, \ldots, e_m$ and $f_1, \ldots, f_n$ are bases of $V, W$ respectively then \(\{e_i \otimes f_j : 1 \leq i \leq m, 1 \leq j \leq n\}\) is a basis of $V \otimes W$.

Proof. (Span.) Any $v \otimes w$ can be expressed (hence so can any element of $V \otimes W$) as $v = \sum_i \alpha_i e_i, w = \sum_j \beta_j f_j \Rightarrow v \otimes w = \sum_{i,j} \alpha_i \beta_j e_i \otimes f_j$.

(Independence.) Find a linear functional $\phi$ sending $e_i \otimes f_j$ to 1 and all the rest to 0. For, take dual basis $\{\varepsilon_i\}, \{\phi_j\}$ to the above. Define $\phi(v \otimes w) = \varepsilon_i(v) \phi_j(w)$ and check $\phi(e_i \otimes f_j) = 1$, other = 0.

(9.13) Lemma. There is a ‘natural’ (basis independent) isomorphism in each of the following.

(i) $V \otimes W \cong W \otimes V$
(ii) $U \otimes (V \otimes W) \cong (U \otimes V) \otimes W$
(iii) $(U \otimes V) \otimes W \cong (U \otimes W) \otimes (V \otimes W)$

Proof. (i) $v \otimes w \mapsto w \otimes v$ and extend linearly. It’s well-defined: $(v, w) \mapsto w \otimes v$ is a bilinear map $V \times W \to W \otimes V$. So by the universal property $v \otimes w \mapsto w \otimes v$ gives a well-defined linear map.

(ii) $u \otimes (v \otimes w) \mapsto (u \otimes v) \otimes w$ and extend linearly. It’s well-defined: fix $u \in U$, then $(v, w) \mapsto (u \otimes v) \otimes w$ is bilinear, so get $v \otimes w \mapsto (u \otimes v) \otimes w$.

Varying $u$, $(u, v \otimes w) \mapsto (u \otimes v) \otimes w$ is a well-defined bilinear map $U \times (V \otimes W) \to (U \otimes V) \otimes W$. Hence, get linear map $u \otimes (v \otimes w) \mapsto (u \otimes v) \otimes w$.

(iii) Similar. (See Telemann, chapter 6.)

(9.14) Lemma. Let $\dim V, \dim W < \infty$. Then $\text{Hom}(V, W) \cong V^* \otimes W$ naturally as G-spaces, if $V, W$ are both G-spaces.

Proof. The natural map $V^* \times W \to \text{Hom}(V, W)$, $(\alpha, w) \mapsto (\phi : v \mapsto \alpha(v)w)$ is bilinear, so $\alpha \otimes w \mapsto \phi$, extended linearly, is a linear map, $V^* \otimes W \to \text{Hom}(V, W)$.

It’s bijective as it takes basis to basis: $\varepsilon_i \otimes f_j \mapsto (E_{ji} : \varepsilon_i \mapsto f_j)$.

Returning to the proof of orthogonality at the end of chapter 6: the missing link was to observe that $U = \text{Hom}(V', V) \cong (V')^* \otimes V$, hence $\chi_n(g) = \chi_{(V')^* \otimes V}(g) = \chi_{V^*}(g^{-1}) \chi_V(g)$. 29
Symmetric and exterior powers

$V$ an $F$-space, $\dim V = d$, basis $\{e_1, \ldots, e_d\}$, $n \in \mathbb{N}$. Then $V^{\otimes n} = V \otimes \ldots \otimes V$ ($n$ times), of dimension $d^n$.

Note, $S_n$ acts on $V^{\otimes n}$: for $\sigma \in S_n$, $\sigma(v_1 \otimes \ldots \otimes v_n) = v_{\sigma(1)} \otimes \ldots \otimes v_{\sigma(n)}$, and extend linearly (‘place permutations’).

The $S_n$-action commutes with any $G$-action on $V$.

**Definition.**

The symmetric powers, $S^nV = \{x \in V^{\otimes n} : \sigma(x) = x \text{ for all } \sigma \in S_n\}$.

The exterior powers, $\Lambda^nV = \{x \in V^{\otimes n} : \sigma(x) = \text{sgn}(\sigma)x \text{ for all } \sigma \in S_n\}$.

These are $G$-subspaces of $V^{\otimes n}$, but if $n > 2$ then there are others obtained from the $S_n$-action.

**Exercises.** Basis for $S^nV$ is $\left\{ \frac{1}{n!} \sum_{\sigma \in S_n} v_{i_{\sigma(1)}} \otimes \ldots \otimes v_{i_{\sigma(n)}} : 1 \leq i_1 \leq \ldots \leq i_n \leq d \right\}$.

Basis for $\Lambda^nV$ is $\left\{ \frac{1}{n!} \sum_{\sigma \in S_n} \text{sgn}(\sigma)v_{i_{\sigma(1)}} \otimes \ldots \otimes v_{i_{\sigma(n)}} : 1 \leq i_1 < \ldots < i_n \leq d \right\}$.

So $\dim S^nV = \binom{d + n - 1}{n}$ and $\dim \Lambda^nV = \binom{d}{n}$.

**Definition.** Let $T^nV = V^{\otimes n} = V \otimes \ldots \otimes V$.

The tensor algebra of $V$ is $T(V) = \bigoplus_{n \geq 0} T^nV$, where $T^0V = \{0\}$ – an $F$-space with obvious addition and scalar multiplication.

There is a product: for $x \in T^nV$, $y \in T^mV$, get $x.y := x \otimes y \in T^{n+m}V$, thus giving a graded algebra (with product $T^nV \otimes T^mV \to T^{n+m}V$).

Finally, define:

$S(V) = T(V)/(\text{ideal generated by } u \otimes v - v \otimes u)$ – the symmetric algebra,

$\Lambda(V) = T(V)/(\text{ideal generated by } v \otimes v)$ – the exterior algebra.

**Character ring**

$\mathcal{C}(G)$ is a ring, so the sum and product of characters are class functions. This chapter verified that they are in fact characters afforded by the sum and tensor product of their corresponding representations.

**Definition.** The $\mathbb{Z}$-submodule of $\mathcal{C}(G)$ spanned by the irreducible characters of $G$ is the character ring of $G$, written $R(G)$.

Elements of $R(G)$ are called difference/generalised/virtual characters.

$\psi \in R(G) : \psi = \sum_{\chi \text{irred}} n_\chi \chi$, $n_\chi \in \mathbb{Z}$.
$R(G)$ is a commutative ring, and any generalised character is a difference of two characters. I.e., $\psi = \alpha - \beta$, $\alpha, \beta$ characters, where $\alpha = \sum_{n_{\chi} \geq 0} n_{\chi} \chi$, $\beta = -\sum_{n_{\chi} < 0} n_{\chi} \chi$.

The $\{\chi_i\}$ form a $\mathbb{Z}$-basis for $R(G)$, as free $\mathbb{Z}$-module.

Suppose $\alpha \in R(G)$ and $\langle \alpha, \alpha \rangle = 1$. Then $\alpha(1) > 0$ implies $\alpha$ is the character of an irreducible representation of $G$.

**Proof.** Let the irreducible characters of $G$ be $\chi_1, \ldots, \chi_k$. Then $\alpha = \sum n_i \chi_i$. So $\langle \alpha, \alpha \rangle = \sum n_i^2 = 1$, so exactly one $n_i = \pm 1$. But $\alpha(1) > 0$, so one $n_i = 1$ and the rest are 0.

Henceforth we don’t distinguish between a character and its negative, and we often study generalised characters of norm 1 ($\langle \alpha, \alpha \rangle = 1$) rather than just irreducible characters.
10. Induction and Restriction

Throughout, \( H \leq G \).

(10.1) Definition (Restriction). Let \( \rho : G \to GL(V) \) be a representation affording \( \chi \). Can think of \( V \) as a \( H \)-space by restricting attention to \( h \in H \).

Get \( \text{Res}^G_H \rho : H \to GL(V) \), the restriction of \( \rho \) to \( H \). (Also written \( \rho|_H \) or \( \rho_H \).)

It affords the character \( \text{Res}^G_H \chi \). (Also written \( \chi|_H \) or \( \chi_H \).)

(10.2) Lemma. If \( \psi \) is any non-zero character of \( H \), then there exists an irreducible character \( \chi \) of \( G \) such that

\[
\begin{align*}
\bullet & \psi \subset \text{Res}^G_H \chi \\
\bullet & \psi \text{ is a constituent of } \text{Res}^G_H \chi \\
\bullet & \langle \text{Res}^G_H \chi, \psi \rangle_H \neq 0
\end{align*}
\]

3 ways of saying the same thing

Proof. List the irreducible characters of \( G \): \( \chi_1, \ldots, \chi_k \). Recall \( \chi_{\text{reg}} \) from (5.9).

\[
0 \neq \frac{|G|}{|H|} \psi(1) = \langle \chi_{\text{reg}|_H}, \psi \rangle_H = \sum \deg \chi_i \langle \chi_i|_H, \psi \rangle_H
\]

Therefore \( \langle \chi_i|_H, \psi \rangle \neq 0 \) for some \( i \).

(10.3) Lemma. Let \( \chi \) be an irreducible character of \( G \), and let \( \text{Res}^G_H \chi = \sum \chi_i \) with \( \chi_i \) irreducible characters of \( H \), where \( c_i \in \mathbb{Z}_{\geq 0} \).

Then \( \sum c_i^2 \leq |G : H| \), with equality iff \( \chi(g) = 0 \) for all \( g \in G \setminus H \).

Proof. \( \sum c_i^2 = \langle \text{Res}^G_H \chi, \text{Res}^G_H \chi \rangle_H = \frac{1}{|H|} \sum_{h \in H} |\chi(h)|^2 \).

But \( 1 = \langle \chi, \chi \rangle_G = \frac{1}{|G|} \sum_{g \in G} |\chi(g)|^2 \)

\[
= \frac{1}{|G|} \left( \sum_{h \in H} |\chi(h)|^2 + \sum_{g \in G \setminus H} |\chi(g)|^2 \right)
\]

\[
= \frac{|H|}{|G|} \sum c_i^2 + \frac{1}{|G|} \sum_{g \in G \setminus H} |\chi(g)|^2 \geq 0, \quad \text{and } 0 \iff \chi(g) = 0 \forall g \in G \setminus H
\]

Therefore \( \sum c_i^2 \leq |G : H| \), with equality iff \( \chi(g) = 0 \) for all \( g \in G \setminus H \).

Example. \( G = S_5 \), \( H = A_5 \), \( \psi_i = \text{Res}^G_H \chi_i \).

\[
\begin{array}{cccccc}
\text{deg} \chi_i & 1 & 1 & 4 & 4 & 5 & 5 \\
\text{deg} \psi_i & 1 & 4 & 5 & & & \\
\end{array}
\]

General fact about normal subgroups: splits into constituents of equal degree (Clifford’s Theorem)
(10.4) Definition (Induction). If $\psi$ is a class function of $H$, define

$$
\psi^G = \text{Ind}_H^G \psi(g) = \frac{1}{|H|} \sum_{x \in G} \psi(x^{-1}gx),
$$

where $\psi(y) = \begin{cases} \psi(y) & y \in H \\ 0 & y \notin H \end{cases}$. 

(10.5) Lemma. If $\psi$ is a class function of $H$, then $\text{Ind}_H^G \psi$ is a class function of $G$, and $\text{Ind}_H^G \psi(1) = |G : H| \psi(1)$.

**Proof.** Clear, noting that $\text{Ind}_H^G \psi(1) = \frac{1}{|H|} \sum_{x \in G} \psi(1) = |G : H| \psi(1)$. \hfill $\square$

Let $n = |G : H|$. Let $t_1, t_2, \ldots, t_n$ be a left transversal of $H$ in $G$ (i.e., a complete set of coset representatives), so $t_1H = H, t_2H, \ldots, t_nH$ are precisely the left cosets of $H$ in $G$.

(10.6) Lemma. Given a transversal as above, $\text{Ind}_H^G \psi(g) = \sum_{i=1}^n \psi(t_i^{-1}gt_i)$.

**Proof.** For $h \in H$, $\psi ((t_ih)^{-1}g(t_ih)) = \psi (t_i^{-1}gt_i)$, as $\psi$ is a class function of $H$. \hfill $\square$

(10.7) Theorem (Frobenius Reciprocity). $\psi$ a class function on $H$, $\phi$ a class function on $G$. Then

$$
\langle \text{Res}_H^G \phi, \psi \rangle_H = \langle \phi, \text{Ind}_H^G \psi \rangle_G.
$$

**Proof.**

$$
\langle \phi, \psi^G \rangle_G = \frac{1}{|G|} \sum_{g \in G} \phi(g) \psi^G(g) = \frac{1}{|G|} \sum_{g,a \in G} \phi(g) \psi(x^{-1}gx) = \frac{1}{|G|} \sum_{x,y \in G} \phi(y) \psi(y) \quad \text{(independent of } x) = \frac{1}{|H|} \sum_{y \in H} \phi(y) \psi(y) = \langle \phi_H, \psi \rangle_H \quad \square
$$

(10.8) Corollary. If $\psi$ is a character of $H$ then $\text{Ind}_H^G \psi$ is a character of $G$.

**Proof.** Let $\chi$ be an irreducible character of $G$.

By (10.7), $\langle \text{Ind}_H^G \psi, \chi \rangle_G = \langle \psi, \text{Res}_H^G \chi \rangle \in \mathbb{Z}_{\geq 0}$, since $\psi, \text{Res}_H^G \chi$ are characters.

Hence $\text{Ind}_H^G \psi$ is a linear combination of irreducible characters, with positive coefficients, hence a character. \hfill $\square$

(10.9) Lemma. Let $\psi$ be a character (or even a class function) of $H \leq G$ and let $g \in G$. Let $C_C(g) \cap H = \bigcup_{i=1}^m C_H(x_i)$ (disjoint union), where $x_i$ are representatives of the $m$ $H$-conjugacy classes of elements of $H$ conjugate to $g$.

Then, for $m = 0$, $\text{Ind}_H^G \psi(g) = 0$, and for $m \geq 1$, $\text{Ind}_H^G \psi(g) = |C_C(g)| \sum_{i=1}^m \frac{\psi(x_i)}{|C_H(x_i)|}$. 

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**Diversion.** Let $H, K \leq G$. A double coset of $H$ and $K$ in $G$ is a set of the form $HxK = \{hxk : h \in H, k \in K\}$ for some $x \in G$.

**Facts.** Two double cosets are either disjoint or equal, and

$$|HxK| = \frac{|H||K|}{|H \cap xKx^{-1}|} = \frac{|H||K|}{|xHx^{-1} \cap K|}$$

**Proof of (10.9).** If $m = 0$ then \(\{x \in G : x^{-1}gx \in H\} = \emptyset\), and then \(\text{Ind}_H^G \psi(g) = 0\) by definition.

Let \(m > 0\). Let \(X_i = \{x \in G : x^{-1}gx \in H\}\) and is conjugate in $H$ to $x_i$, for \(1 \leq i \leq m\). The \(X_i\) are pairwise disjoint and their union is \(\{x \in G : x^{-1}gx \in H\}\).

By definition,

$$\text{Ind}_H^G \psi(g) = \frac{1}{|H|} \sum_{x \in G} \psi(x^{-1}gx) = \frac{1}{|H|} \sum_{i=1}^{m} \sum_{x \in X_i} \psi(x^{-1}gx)$$

$$= \frac{1}{|H|} \sum_{i=1}^{m} \sum_{x \in X_i} \psi(x_i) = \sum_{i=1}^{m} \frac{|X_i|}{|H|} \psi(x_i).$$

We need to calculate \(\frac{|X_i|}{|H|}\).

Fix \(1 \leq i \leq m\) and choose \(g_i \in G\) such that \(g_i^{-1}gg_i = x_i\). So for all \(c \in C_G(g)\) and \(h \in H\) we have

\((cg_ih)^{-1}g(cg_ih) = h^{-1}g_i^{-1}c^{-1}gcg_ih = h^{-1}g_i^{-1}gg_ih = h^{-1}x_ih,\)

i.e. \(cg_ih \in X_i\), and hence \(C_G(g)g_iH \subseteq X_i\).

Conversely, for \(x \in X_i\), we have \(x^{-1}gx = h^{-1}x_ih = h^{-1}(g_i^{-1}gg_i)h\) for some \(h \in H\). So \(xh^{-1}g_i^{-1} \in C_G(g)\), and hence \(x \in C_G(g)g_iH \subseteq C_G(g)g_iH\).

Thus \(C_G(g)g_iH = X_i\), so \(|X_i| = |C_G(g)g_iH| = \frac{|C_G(g)||H|}{|H \cap g_i^{-1}C_G(g)g_i|}\).

But \(g_i^{-1}C_G(g)g_i = C_G(g_i^{-1}gg_i) = C_G(x_i)\).

So \(|X_i| = |H : H \cap C_G(x_i)||C_G(g)| = |H : C_G(x_i)||C_G(g)|\).

So \(\frac{|X_i|}{|H|} = \frac{|C_G(g)|}{|C_G(x_i)|}\), giving the result. \(\square\)

**Lemma.** If \(\psi = 1_H\), the principal character of $H$, then \(\text{Ind}_H^G 1_H = \pi_X\), the permutation character of $G$ on the set $X$ of left cosets of $H$ in $G$. 

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Proof. \[ \text{Ind}^G_H 1_H(g) = \sum 1_H(t_i^{-1}gt_i) \] (where the \( t_i \) form a transversal)
\[ = \left| \{ i : t_i^{-1}gt_i \in H \} \right| \]
\[ = \left| \{ i : g \in t_iHt_i^{-1} \} \right| \] ← stabiliser in \( G \) of the point \( t_iH \in X \)
\[ = \left| \text{fix}_X(g) \right| = \pi_X \] (see (7.1)) \( \square \)

Remark. Recalling (7.3):
\[ \langle \pi_X, 1_G \rangle_G = \langle \text{Ind}^G_H 1_H, 1_G \rangle_G = \langle 1_H, \text{Res}^G_H 1_G \rangle_H = \langle 1_H, 1_H \rangle_H = 1. \]

Examples. (a) Recall (7.9), \( G = S_5 \) acting on \( X = \) the set of Sylow 5-subgroups of \( G \).
\( \pi_X = \text{Ind}^G_H 1_H \), where \( H = \langle (12345), (2354) \rangle \). Note \( |H| = 20 \).
\[ \begin{array}{c|cccccc}
H\text{-ccls} & 1 & (12345) & (2354) & (25)(34) & (2453) & (25)(34) \\
size & 1 & 4 & 5 & 5 & 5 & 5 \\
\end{array} \]
\[ \begin{array}{c|cccccc}
G\text{-ccls} & 1 & (12)(34) & (123) & (12345) & (12) & (123)(45) & (1234) \\
size & 1 & 15 & 20 & 24 & 10 & 20 & 30 \\
\end{array} \]
\[ \pi_X(2354) = \frac{120}{20} \left( \frac{5}{20} + \frac{5}{20} \right) = 4 \left( \frac{1}{4} + \frac{1}{4} \right) = 2 \]
\[ \pi_X((25)(34)) = \frac{120}{20} \left( \frac{5}{20} \right) = 8 \left( \frac{1}{4} \right) = 2. \] (All elements (25)(34) are conjugate in \( H \).)
(b) Recall (2.17) and (7.8). \( H = C_4 = \langle (1234) \rangle \leq G = S_4 \), index 6.
Character of induced representation \( \text{Ind}^S_4 \langle \alpha \rangle \), where \( \alpha \) is faithful 1-dimensional representation of \( C_4 \). If \( \alpha((1234)) = i \) then character of \( \alpha \) is:
\[ \chi_\alpha = \begin{array}{c|cccc}
1 & (1234) & (13)(24) & (1432) \\
i & 1 & -1 & -i \\
\end{array} \]
Induced representations:
\[ \begin{array}{c|cccccc}
\text{size} & 1 & 6 & 8 & 3 & 6 & 0 \\
\text{ccls} & 1 & (12) & (123) & (1234) & (1234) & \\
\text{Ind}^S_4 \langle \alpha \rangle & 1 & 6 & 0 & 0 & -2 & 0 \\
\end{array} \]
For (12)(34), only one of 3 elements in \( S_4 \) that it’s conjugate to lies in \( H \). So \( \text{Ind}^S_4 \langle \alpha \rangle = 8 \left( -\frac{1}{4} \right) = -2 \).
(1234) is conjugate to 6 elements of \( S_4 \), of which 2 are in \( C_4 \) (viz. (1234), (1432)).
So \( \text{Ind}^S_4 \langle \alpha \rangle = 4 \left( \frac{1}{4} - \frac{1}{4} \right) = 0 \).

Induced modules
\( H \leq G \), index \( n \). \( t_1, t_2, \ldots, t_n \) a transversal – i.e. \( H, t_2H, \ldots, t_nH \) are the left cosets of \( H \) in \( G \). Let \( W \) be an \( H \)-space.

(10.11) Definition. Let \( V = W \oplus t_2 \otimes W \oplus \ldots \oplus t_n \otimes W \), where \( t_i \otimes W = \{ t_i \otimes w : w \in W \} \).
(‘Essentially tensored group algebra with \( W \).’)
So \( \dim V = n \dim W \) and we write \( V = \text{Ind}^G_H W \).

\( G \)-action. \( g \in G \), for all \( i \), there exists a unique \( j \) with \( t_j^{-1}gt_i \in H \) (namely \( t_jH \) is the unique coset which contains \( gt_i \)).
Define $g(t, w) = t_j \left( t_j^{-1} g t_i \right) w$. (Drop the $\otimes$s, so $t_i w := t_i \otimes w$.) Check this is a $G$-action:

\[
g_1 \left( g_2 t_i w \right) = g_1 \left( t_j \left( t_j^{-1} g_2 t_i \right) w \right)
\]

(3 unique $j$ s.t. $g_2 t_i H = t_j H$)

\[
= t_j \left( t_j^{-1} g_1 t_j \left( t_j^{-1} g_2 t_i \right) w \right)
\]

(3 unique $j$ s.t. $g_1 t_j H \in t_j H$)

\[
= t_j \left( t_j^{-1} \left( g_1 g_2 \right) t_i \right) w
\]

\[
= \left( g_1 g_2 \right) \left( t_j t_i w \right)
\]

$\ell$ is unique with $(g_1 g_2) t_i H \in t_\ell H$.

It has the right character (still dropping the $\otimes$) $g : t_i w \mapsto t_j \left( t_j^{-1} g t_i \right) w$.

So the contribution to the character is 0 unless $j = i$, i.e. unless $t_i^{-1} g t_i \in H$, then it contributes $\psi(t_i^{-1} g t_i)$, i.e. $\text{Ind}^G_H \psi(g) = \sum_{i=1}^n \psi \left( t_i^{-1} g t_i \right)$, thus agreeing with (10.6).

**Example.** Module-theoretic version of (10.10) states: $\text{Ind}^G_H \left( C \right) = C$ $X$, where $X = G/H$.

In particular, $\text{Ind}_1^G \left( C \right) = \rho_{\text{reg}}$.

**Remarks (non-examinable).** (1) There is also a ‘Frobenius reciprocity’ for modules: for $W$ a $H$-space, $V$ a $G$-space, $\text{Hom}_H(W, \text{Res}^G_H V) \cong \text{Hom}_G(\text{Ind}^G_H W, V)$ naturally, as vector spaces.

This is an example of a ‘Nakayama relation’. See Telemann 15.9 – works over general fields.

(2) Tensor products of modules over rings. In (10.11), $V = FG \otimes_{FH} W$.

Replace $FG$ by $R$, $FH$ by $S$, and try to generalise. In general, given rings $R, S$, and modules $U$ an $(R, S)$-bimodule and $W$ a left $S$-module, then $U \otimes W$ is a left $R$-module with balanced map $t : U \times W \to U \otimes W$ such that any balanced map $f : U \times W \to X$, any left $R$-module $X$ can be factored through $t$.

\[
U \times W \xrightarrow{t} U \otimes W \xrightarrow{f} X
\]

‘Balanced’ means

\[
f(u_1 + u_2, w) = f(u_1, w) + f(u_2, w)
\]

\[
f(u, w_1 + w_2) = f(u, w_1) + f(u, w_2)
\]

\[
f(\lambda u, w) = f(u, \lambda w) \quad \text{for all } \lambda \in S
\]

Then $\text{Ind}^G_H W = FG \otimes W$ is now a well-defined $FG$-module, since $W$ is a left $FH$-module, $FG$ is $(FG, FH)$-bimodule. (Alperin-Bell.)
11. Frobenius Groups

(11.1) Frobenius Theorem (1891). \( G \) a transitive permutation group on a set \( X \), with \(|X| = n\). Assume that each non-identity element of \( G \) fixes at most one element of \( X \). Then

\[
K = \{1\} \cup \{g \in G : g\alpha \neq \alpha \text{ for all } \alpha \in X\}
\]

is a normal subgroup of \( G \) of order \( n \).

Proof. (Suzuki, Collins (book).) Required to prove \( K \unlhd G \).

Let \( H = G_\alpha \) (stabiliser of \( \alpha \in X \)), so conjugates of \( H \) are the stabilisers of single elements of \( X \), as \( Gg\alpha = gG_\alpha g^{-1} \). No two conjugates can share a non-identity element (hypothesis).

So \( H \) has \( n \) distinct conjugates and \( G \) has \( n(|H| - 1) \) elements that fix exactly one element of \( X \). But \( |G| = |X||H| = n|H| \). (\( X \) and \( G/H \) are isomorphic \( G \)-sets, as the action is transitive), hence \( |K| = |G| - n(|H| - 1) = n \).

Let \( 1 \neq h \in H \). Suppose \( h = gh'g^{-1} \), some \( g \in G, h' \in H \). Then \( h \) lies in \( G = G_\alpha \) and \( gHg^{-1} = G_{g\alpha} \). By hypothesis, \( g\alpha = \alpha \), hence \( g \in H \). So \( H \cap ccl_G(h) \) is precisely \( ccl_H(h) \).

Similarly, if \( g \in C_G(h) \) then \( h = ghg^{-1} \in G_{g\alpha} \) hence \( g \in H \), i.e. \( C_G(h) = C_H(h) \).

Every element of \( G \) lies either in \( K \) or in one of the \( n \) stabilisers, each of which is conjugate to \( H \). So every element of \( G \setminus K \) is conjugate with a non-1 element of \( H \). So

\[
\{1, h_2, \ldots, h_t, y_1, \ldots, y_u\}
\]

is a set of conjugacy class representatives for \( G \).

Problem. To show \( K \subseteq G \).

Take \( \theta = 1_G, \{1_H = \psi_1, \psi_2, \ldots, \psi_t\} \) irreducible characters of \( H \). Fix some \( 1 \leq i \leq t \). Then if \( g \in G \),

\[
\text{Ind}_H^G \psi_i(g) = \begin{cases} 
|G:H| \psi_i(1) = n\psi_i(1) & g = 1 \\
\psi_i(h_j) & g = h_j \ (2 \leq j \leq t) \\
0 & g = y_k \ (1 \leq k \leq u) 
\end{cases}
\]

\( C_G(h_j) = C_H(h_j) \) \& (10.9)

Fix some \( 2 \leq i \leq t \) and put \( \theta_i = \psi_i^G - \psi_i(1)\psi_1^G + \psi_i(1)\theta_1 \in R(G) \), by (9.16).

Values for \( 2 \leq j \leq t, 1 \leq k \leq u \):

<table>
<thead>
<tr>
<th>\psi_i^G</th>
<th>\psi_i(1)</th>
<th>\psi_i(h_j)</th>
<th>y_k</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>n\psi_i(1)</td>
<td>\psi_i(h_j)</td>
<td>0</td>
</tr>
<tr>
<td>\psi_i(1)\psi_1^G</td>
<td>n\psi_i(1)</td>
<td>\psi_i(1)</td>
<td>0</td>
</tr>
<tr>
<td>\psi_i(1)\theta_1</td>
<td>\psi_i(1)</td>
<td>\psi_i(1)</td>
<td>\psi_i(1)</td>
</tr>
<tr>
<td>\theta_1</td>
<td>\psi_i(1)</td>
<td>\psi_i(h_j)</td>
<td>\psi_i(1)</td>
</tr>
</tbody>
</table>
\[
\langle \theta_i, \theta_i \rangle = \frac{1}{|G|} \sum_{g \in G} |\theta_i(g)|^2
\]
\[
= \frac{1}{|G|} \left( \sum_{g \in K} |\theta_i(g)|^2 + \sum_{\alpha \in \mathcal{X}} \sum_{1 \neq g \in G_{\alpha}} |\theta_i(g)|^2 \right)
\]
\[
= \frac{1}{|G|} \left( n\psi_i^2(1) + n \sum_{1 \neq h \in H} |\theta_i(h)|^2 \right)
\]
\[
= \frac{1}{|H|} \sum_{h \in H} |\psi_i(h)|^2
\]
\[
= \langle \psi_i, \psi_i \rangle = 1
\]
(row orthogonality of irreducible $H$-characters)

By (9.17) either $\theta_i$ or $-\theta_i$ is an irreducible character of $G$, since $\theta_i(1) > 0$, it is $\theta_i$. Let $\theta = \sum_{i=1}^t \theta_i(1)\theta_i$. Column orthogonality \(\Rightarrow\) $\theta(h) = \sum_{i=1}^t \psi_i(1)\psi_i(h) = 0$ (\(1 \neq h \in H\)) and for any $y \in K$, $\theta(y) = \sum \psi_i^2(1) = |H|$. 

So $\theta(g) = \begin{cases} 
|H| & \text{if } g \in K \\
0 & \text{if } g \notin K
\end{cases}$

Therefore $K = \{g \in G : \theta(g) = \theta(1)\} \leq G$. \(\square\)

(11.2) Definition. A Frobenius group is a group $G$ having a subgroup $H$ such that $H \cap H^g = 1$ for all $g \notin H$. $H$ is a Frobenius complement.

(11.3) Any finite Frobenius group satisfies the hypothesis of (11.1). The normal subgroup $K$ is the Frobenius kernel of $G$.

If $G$ is Frobenius and $H$ a complement then the action of $G$ on $G/H$ is faithful and transitive. If $1 \neq g \in G$ fixes $xH$ and $yH$ then $g \in xHx^{-1} \cap yHy^{-1}$, which implies that $H \cap (y^{-1}x)H(y^{-1}x)^{-1} \neq 1$, and so $xH = yH$.

Remarks. (i) Thompson (thesis, 1959) worked on the structure of Frobenius groups – e.g. showed that $K$ is nilpotent (i.e., $K$ is the direct product of its Sylow subgroups).

(ii) There is no proof of (11.1) known in which character theory is not used.

(iii*) Show that $G = K \rtimes H$, semi-direct product.
12. Mackey Theory

This describes restriction to a subgroup \( K \leq G \) of an induced representation \( \in \mathbb{W} \). \( K, H \) are unrelated but usually we take \( K = H \), in which case we can tell when \( \text{Ind}^G_H \mathbb{W} \) is irreducible.

**Special case:** \( \mathbb{W} = 1 \) (trivial \( H \)-space, dim 1). Then by (10.10) \( \text{Ind}^G_H 1 = \) permutation representation of \( G \) on \( X = G/H \) (coset action on the set of left cosets of \( H \) in \( G \)).

**Recall.** If \( G \) is transitive on a set \( X \) and \( H = G_\alpha (\alpha \in X) \) then the action of \( G \) on \( X \) is isomorphic to the action on \( G/H \), viz:

\[
(12.1) \quad g_0 \alpha \leftrightarrow gH \quad \text{is a well-defined bijection and commutes with } G\text{-actions.}
\]

I.e., \( x(g_0) = (xg)\alpha \leftrightarrow x(gH) = (xg)H \).

Consider the action of \( G \) on \( G/H \) and restriction to some \( K \leq G \).

**Theorem (Mackey’s Restriction Formula).**

\[
\text{Res}^G_K \text{Ind}^G_H \mathbb{W} = \bigoplus_{g \in K \setminus G/H} \text{Ind}^K_{Hg^{-1} \cap K} W_g,
\]

summed over set of representatives of double cosets.

Now choose \( g_1, \ldots, g_r \) such that \( G = \bigcup Kg_i H \). Let \( W \) be an \( H \)-space, and write \( W_g \) for the \( H_g \)-space with the same underlying vector space as \( W \) of vectors, but with \( H_g \)-action from \( \rho_g(x) = \rho(g^{-1}xg) \) for \( x \in gHg^{-1} \).

We will prove:

**Theorem.** If \( \psi \in \mathcal{C}(H) \), then \( \text{Res}^G_K \text{Ind}^G_H \psi = \sum_{g \in K \setminus G/H} \text{Ind}^K_{Hg} \psi_g \), where \( \psi_g \) is the class function on \( H_g \) given by \( \psi_g(x) = \psi(x^{g^{-1}}) \).

The most useful form for applications is:

**Corollary (Mackey’s Irreducibility Criterion).** \( H \leq G, W \) and \( H \)-space. Then

\[
V = \text{Ind}^G_H W \text{ is irreducible iff}
\]

(i) \( W \) is irreducible, and

(ii) for each \( g \in G \setminus H \), the two \( (gHg^{-1} \cap H) \)-spaces \( W_g \) and \( \text{Res}^H_{Hg} W \) have no irreducible constituents in common. (We say they are disjoint.)
Proof of Corollary. Take \( K = H \) in (12.4), so \( H_g = gHg^{-1} \cap H \). Assume \( W \) is irreducible with character \( \psi \).

\[
\langle \text{Ind}_H^G \psi, \text{Ind}_H^G \psi \rangle = \langle \psi, \text{Res}_H^G \text{Ind}_H^G \psi \rangle \tag{F.R.}
\]

\[
= \sum_{g \in H \backslash G / H} \langle \psi, \text{Ind}_H^G \psi_g \rangle_H \tag{12.5}
\]

\[
= \sum_{g \in H \backslash G / H} \langle \text{Res}_H^G \psi, \psi_g \rangle_{H_g} \tag{F.R.}
\]

\[
= 1 + \sum_{g \in H \backslash G / H} d_g \text{ where } d_g = \langle \text{Res}_H^G \psi, \psi_g \rangle_{H_g}
\]

So to get irreducibility we need all the \( d_g = 0 \). \( \square \)

(12.7) Corollary. If \( H \trianglelefteq G \), assume \( \psi \) is an irreducible character of \( H \). Then \( \text{Ind}_H^G \psi \) is irreducible iff \( \psi \) is distinct from all its conjugates \( \psi_g \) for \( g \in G \setminus H \), where \( \psi_g(h) = \psi(hg^{-1}) = \psi(g^{-1}hg) \).

Proof. Take \( K = H \), so \( H_g = gHg^{-1} \cap H = H \) for all \( g \) (since \( H \trianglelefteq G \)). \( \psi \) is the character of \( H \) conjugate to \( \psi \), so \( \text{Res}_H^G \psi = \psi \) and the \( \psi_g \) are just the conjugates of \( \psi \). \( \square \)

Proof of (12.4). Write \( V = \text{Ind}_H^G W \). Fix \( g \in G \), so \( KgH \in K \backslash G / H \). Observe \( V \) is a direct sum of images of the form \( xW \) (officially \( x \otimes W \), recall), with \( x \) running over representatives of left cosets of \( H \) in \( G \) (see (10.11)). Collect together the images \( xW \) with \( x \in KgH \) (as in (12.3)) and define \( V(g) = \bigoplus_{x \in KgH} xW \).

Now \( V(g) \) is a \( K \)-space and \( \text{Res}_K^G V = \bigoplus_{g \text{ reps of } K \backslash G / H} V(g) \).

We have to prove \( V(g) = \text{Ind}_{H_g}^{K_g} W_g \), as \( K \)-spaces. The subgroup of \( K \) consisting of the elements \( x \) with \( xgW = gW \) is \( H_g = gHg^{-1} \cap K \) (see (12.2)), and \( V(g) = \bigoplus_{x \in K \backslash H_g} x(gW) \).

Hence \( V(g) \cong \text{Ind}_{H_g}^{K_g} (gW) \).

Finally \( W_g \cong gW \) as \( K \)-spaces, as the map \( w \mapsto gw \) is an isomorphism. Hence the assertion. \( \square \)

Examples. (a) Give a direct proof of (12.3). Hint. Write \( G = \bigcup_{g_i \text{ reps of } K \backslash G / H} KgH \), \( (1 \leq i \leq r) \).

Let \( H_{g_i} \) have transversal \( k_{i_1}, \ldots, k_{i_r} \) in \( K \). Then \( \{k_{ij}g_i : 1 \leq i \leq r, 1 \leq j \leq r_i \} \) is a transversal of \( K \) in \( G \). Then compute \( \text{Ind}_H^G \psi(k) \).

(b) (Examples sheet 3, question 4.) \( C_n \triangleright D_{2n} = \langle x, y : x^n = y^2 = 1, y^{-1}xy = x^{-1} \rangle \).

Mackey says that for any 1-dimensional representation \( \alpha \) of \( C_n \), the 2-dimensional representation \( \text{Ind}_{C_n}^{D_{2n}} \alpha \) is irreducible iff \( \alpha \) is not isomorphic to \( \alpha_y \).

Now \( y^{-1}xy = x^{-1} \), so this says that if \( \alpha(x) = \zeta^i \) \( (\zeta \in \mu_n) \), \( \alpha_y \) is the representation \( \alpha_y(x) = \zeta^{-i} \). So for \( 0 < i < n/2 \) (i.e. when \( e^{2\pi ik/n} \neq e^{-2\pi ik/n} \)) we get a 2-dimensional irreducible representation of \( D_{2n} \) this way.
13. Integrality

(13.1) Definition. \( a \in \mathbb{C} \) is an \textbf{algebraic integer} if it is a root of a monic polynomial in \( \mathbb{Z}[X] \). Equivalently, the subring \( \mathbb{Z}[a] = \{ f(a) : f(x) \in \mathbb{Z}[X] \} \) of \( \mathbb{C} \) is a finitely-generated \( \mathbb{Z} \)-module.

**Fact 1.** The algebraic integers form a subring of \( \mathbb{C} \). (James & Liebeck 22.3)

**Fact 2.** If \( a \in \mathbb{C} \) is both an algebraic integer and a rational number then \( a \in \mathbb{Z} \). (James & Liebeck 22.5)

**Fact 3.** Any subring \( S \) of \( \mathbb{C} \) which is finitely generated as a \( \mathbb{Z} \)-module consists of algebraic integers.

If \( s_1, \ldots, s_n \) are generators of \( S \) as a \( \mathbb{Z} \)-module, let \( a \in S \). Then for all \( i \), there exist \( a_{ij} \in \mathbb{Z} \) with \( as_i = \sum_{j} a_{ij} s_j \). Put \( A = (a_{ij}) \). Then \( Av = av \), where \( v = (s_1, \ldots, s_n)^t \), so \( a \) is a root of the characteristic polynomial of \( A \). Therefore, it’s an algebraic integer.

(13.2) Proposition. If \( \chi \) is a character of \( G \) and \( g \in G \) then \( \chi(g) \) is an algebraic integer.

**Corollary.** There are no entries in the character table of any finite group which are rational but not integers. (Fact 2.)

**Proof of (13.2).** \( \chi(g) \) is the sum of \( n^{th} \) roots of 1 \( (n = |g|) \). Each root of unity is an algebraic integer, and any sum of algebraic integers is an algebraic integer. (Fact 1.) \( \Box \)

Recall from (2.4) the group algebra \( \mathbb{C}G = \{ \sum \alpha_g g : \alpha_g \in \mathbb{C} \} \) of a finite group \( G \), the \( \mathbb{C} \)-space with basis the elements of \( G \). It is also a ring.

List \( C_1 = \{1\}, C_2, \ldots, C_k \), the \( G \)-conjugacy classes. Define the \textbf{class sums}, \( C_j = \sum_{g \in C_j} g \in \mathbb{C}G \).

\( Z(\mathbb{C}G) \) is the \textbf{centre} of \( \mathbb{C}G \) (not the same as \( \mathbb{C}Z(G) \)).

(13.3) Proposition. \( C_1, \ldots, C_k \) is a basis of \( Z(\mathbb{C}G) \). There exist non-negative integers \( a_{ijl} \) \( (1 \leq i, j, l \leq k) \) with \( C_i C_j = \sum a_{ijl} C_l \). These are the \textbf{structure constants} for \( Z(\mathbb{C}G) \).

E.g., \( 1, (12) + (13) + (23), (123) + (132) \) form a basis of \( Z(\mathbb{C}S_3) \).

**Proof.** \( gC_jg^{-1} = C_j \), so \( C_j \in Z(\mathbb{C}G) \). Clearly the \( C_j \) are linearly independent (because the conjugacy classes are pairwise disjoint).

Now suppose \( z \in Z(\mathbb{C}G) \), \( z = \sum_{g \in G} \alpha_g g \). Then for all \( h \in G \) we have \( \alpha_h^{-1}g = \alpha_g \), so the function \( g \mapsto \alpha_g \) is constant on \( G \)-conjugacy classes. Writing \( \alpha_g = \alpha_i \) \( (g \in C_i) \), then \( z = \sum \alpha_i C_j \).

Finally \( Z(\mathbb{C}G) \) is a \( \mathbb{C} \)-algebra (‘vector space over \( \mathbb{C} \) with ring multiplication’), so \( C_i C_j = \sum_{l=1}^{k} a_{ijl} C_l \), as the \( C_j \) span. We claim that \( a_{ijl} \in \mathbb{Z}_{\geq 0} \).

For: fix \( g_\ell \in C_\ell \), then \( a_{ij\ell} = \# \{(x, y) \in C_i \times C_j : xy = g_\ell \} \in \mathbb{Z}_{\geq 0} \). \( \Box \)

(13.4) Definition. Let \( \rho : G \to GL(V) \) be an irreducible representation over \( \mathbb{C} \) affording \( \chi \). Extend by linearity to \( \rho : \mathbb{C}G \to \text{End} V \), an algebra homomorphism. Such a homomorphism of algebras, \( \mathbb{C}G = A \to \text{End} V \) is a \textbf{representation} of \( A \).
Let \( z \in Z(CG) \). Then \( \rho(z) \) commutes with all \( \rho(g) \) (\( g \in G \)), so by Schur’s Lemma \( \rho(g) = \lambda_z I \) for some \( \lambda_z \in \mathbb{C} \). Consider the algebra homomorphism \( w_\chi = w : Z(CG) \to \mathbb{C}, z \mapsto \lambda_z \).

Then \( \rho(C_i) = w(C_i)I \), so \( \chi(1)w(C_i) = \sum_{g \in C_i} \chi(g) = |C_i| \chi(g_i) \) (\( g_i \) a representative of \( C_i \)).

Therefore \( w_\chi(C_i) = \frac{\chi(g_i)}{\chi(1)}|C_i| \).

(13.5) Lemma. The values of \( w_\chi(C_i) = \frac{\chi(g_i)}{\chi(1)}|C_i| \) are algebraic integers.

Proof. Since \( w \) is an algebra homomorphism, have \( w_\chi(C_i)w_\chi(C_j) = \sum_{i=1}^{k} a_{ijl}w_\chi(C_\ell) \), with \( a_{ijl} \in \mathbb{Z}_{\geq 0} \). Thus the span \( \{w_\chi(C_i) : 1 \leq i \leq k \} \) is a subring of \( \mathbb{C} \), so by Fact 3 consists of algebraic integers.

Example. Show that \( a_{ijl} = \# \{(x, y) \in C_i \times C_j : xy = g_\ell \} \) can be obtained from the character table. In fact,

\[
a_{ijl} = \frac{|G|}{|C_G(g_i)||C_G(g_j)|} \sum_{s=1}^{k} \frac{\chi_s(g_i)\chi_s(g_j)\chi_s(g_\ell^{-1})}{\chi_s(1)}.
\]

Hint: use column orthogonality. (See James & Liebeck 30.4.)

(13.6) Theorem. The degree of any irreducible character of \( G \) divides \( |G| \).

I.e., \( \chi_i(1) | |G| \) (\( 1 \leq i \leq k \)).

Proof. Given irreducible \( \chi \). (‘Standard trick: show \( |G|/\chi(1) \in \mathbb{N} \!).’

\[
\frac{|G|}{\chi(1)} = \frac{1}{\chi(1)} \sum_{g \in G} \chi(g)\chi(g^{-1})
= \frac{1}{\chi(1)} \sum_{i=1}^{k} |C_i|\chi(g_i)\chi(g_i^{-1})
= \sum_{i=1}^{k} \frac{|C_i|\chi(g_i)}{\chi(1)} \chi(g_i^{-1})
\]

Now \( \frac{|C_i|\chi(g_i)}{\chi(1)} \) is an algebraic integer by (13.5), and \( \chi(g_i^{-1}) \) is a sum of roots of unity, so is an algebraic integer by (13.2).

Thus \( \frac{|G|}{\chi(1)} \) is an algebraic integer, and since it’s clearly rational, it is an integer.

Examples. (a) If \( G \) is a \( p \)-group then \( \chi(1) \) is a \( p \)-power (\( \chi \) irreducible). If \( |G| = p^2 \) then \( \chi(1) = 1 \) (hence \( G \) is abelian).

(b) No simple group has an irreducible character of degree 2 (see James & Liebeck 22.13).

(c*) In fact, if \( \chi \) is irreducible then \( \chi(1) \) divides \( |G|/|Z| \) (Burnside).

(d) \( G = S_n \) : every prime \( p \) dividing the degree of an irreducible character of \( G \) also divides \( n! \). Hence \( p \leq n \).
(13.7) **Theorem (Burnside).** If $\chi$ is irreducible, then $\chi(1)$ divides $\frac{|G|}{|Z|}$.

**Proof.** Let $\rho : G \to GL(V)$ be a representation with character $\chi$. For any $m$, consider $\rho_m : \rho \otimes_m : G^m \to GL(\bigotimes^m V)$.

Now $\ker \rho_m$ contains the subgroup $Z'_m = \{(g_1, \ldots, g_m) \in Z^m : g_1 \cdots g_m = 1\}$.

If $\rho$ is irreducible then so is $\rho_m$ by (9.11), and $\dim \rho_m = (\dim \rho)^m |G^m / Z'_m| = \frac{|G|^m}{|Z'|^{m-1}}$.

This is true for any $m$, so $\dim \rho$ divides $\frac{|G|}{|Z|}$. (Check via prime factorisation.)
14. Burnside’s $p^aq^b$ Theorem

(14.1) Theorem (Burnside, 1904). $p, q$ primes. Let $|G| = p^aq^b$ where $a, b \in \mathbb{Z}_{>0}$, with $a + b \geq 2$. Then $G$ is not simple.

Remarks. (1) In fact, even more is true: $G$ is soluble. That is, there exists a chain $G = G^0 \triangleright G^1 \triangleright \cdots \triangleright G^r = \{1\}$ such that $G^i/G^{i+1}$ is abelian for all $i$.

(2) The result is best possible: $A_5$ is simple, and $60 = 2^2.3.5$.

(3) If either $a$ or $b$ is $0$ then $|G| = p$-power and we know $Z(G) \neq 1$. Then there is $g \in Z$, $|g| = p$ and $(g) \not\trianglelefteq G$, with $(g) \neq 1$ or $G$.

(14.2) Proposition. $\chi$ an irreducible $\mathbb{C}$-character of $G$, $C$ a $G$-conjugacy class, $g \in G$ such that $(\chi(1), |C|) = 1$. Then $|\chi(g)| = \chi(1)$ or $0$.

Proof. There are $a, b \in \mathbb{Z}_{>0}$ such that $a\chi(1) + b|C| = 1$. Define $\alpha = a\chi(g) + b\chi(g)|C| = \chi(g)/\chi(1)$.

Then $\alpha$ is an algebraic integer, so the assertion follows from:

(14.3) Lemma. Assume $\alpha = \frac{1}{m} \sum_{i=1}^{m} \lambda_i$ is an algebraic integer with $\lambda_j^m = 1$ for all $j$, some $n$.

Then $|\alpha| = 1$.

For (14.2), we take $n = |g|$, $m = \chi(1)$.

Proof (non-examinable). Assume $|\alpha| \neq 0$. Now $\alpha \in F = \mathbb{Q}(\varepsilon)$ where $\varepsilon = e^{2\pi i/n}$ and $\lambda_j \in F$ for all $j$.

Let $G = \text{Gal}(F/\mathbb{Q})$. Observe $\{\beta \in F : \beta^\sigma = \beta \text{ for all } \sigma \in G\} = F^G = \mathbb{Q}$. (Result from Galois Theory.)

Consider the norm $N(\alpha)$ of $\alpha$, namely the product of all the Galois conjugates $\alpha^\sigma$ ($\sigma \in G$). The norm $\in \mathbb{Q}$ because it’s fixed by all of $G$. It’s an algebraic integer (all Galois group conjugates of an algebraic integer are algebraic integers). Hence $N(\alpha) \in \mathbb{Z}$.

But $N(\alpha) = \prod_{\sigma \in G} \alpha^\sigma$ is a product of expressions $\sum_{m} \frac{1}{m} \in \mathbb{C}$ of absolute value $\leq 1$.

Hence the norm must be $\pm 1$, hence $|\alpha| = 1$. \qed

(14.4) Theorem. If in a finite group $G$ the number of elements in a conjugacy class $C \neq \{1\}$ is a $p$-power, then $G$ is not non-abelian simple.

Remark. This implies (14.1). Assume $a > 0, b > 0$. Let $Q \in \text{Syl}_q(G)$. Then $Z(Q) \neq 1$, so choose $1 \neq g \in Z(Q)$. So $C_G(g) \supseteq Q$. Therefore $|C(g)| = |Q : C_G(g)| = p^r$ (some $r$).

Hence if $p^r = 1$ then $g \in Z(G)$. Therefore $Z(G) \neq 1$ (so not simple). If $p^r$ then $G$ is not simple (by (14.4)).

Proof of (14.4). Assume that $G$ is non-abelian simple, and let $1 \neq g \in G$ with $|C_G(g)| = p^r$. 

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By column orthogonality, $0 = \sum_{\chi \text{ irreducible of } G} \chi(1)\chi(g) - (*)$

$G$ is non-abelian simple, so $|\chi(g)| \neq \chi(1)$ for any irreducible $\chi \neq 1$. By (14.2), for any irreducible character $\chi \neq 1$ of $G$, we have $p|\chi(1)$ or $\chi(g) = 0$.

Deleting zero terms in $(*)$, $0 = 1 + p \sum_{\chi \text{ irreducible}} \frac{\chi(1)}{p} \chi(g)$.

Thus $1/p$ is an algebraic integer, since $1/p \in \mathbb{Q}$, hence $1/p \in \mathbb{Z}$. Contradiction. \qed

Remarks. (a) In 1911, Burnside conjectured that if $|G|$ is odd then $G$ is not non-abelian simple. Only proved in 1963 by Feit & Thompson, a result which began the Classification of Finite Simple Groups. The Classification only ended in 2005.

(b) A group-theoretic proof given only in 1972 (H. Bender)
15. Representations of Topological Groups

(15.1) A **topological group** is a group which is also a topological space such that the group operations \( G \times G \to G, (h,g) \mapsto hg \) and \( G \to G, g \mapsto g^{-1} \) are continuous. It is **compact** if it is so as a topological space.

(15.2) **Basic examples.** (a) \( GL_n(\mathbb{R}), GL_n(\mathbb{C}) \) are open subspaces of \( \mathbb{R}^{n^2} \) or \( \mathbb{C}^{n^2} \).

(b) \( G \) finite, discrete topological. Also compact.

(c) \( G = S^1 = U(1) = \{ g \in \mathbb{C} : |g| = 1 \} \).

(d) \( O(n) = \{ A \in GL_n(\mathbb{R}) : AA^t = I \} \) – orthogonal group. Compact: set of orthonormal bases for \( \mathbb{R}^n = \{ (e_1, \ldots, e_n) \in \mathbb{R}^n \times \cdots \times \mathbb{R}^n : \langle e_i, e_j \rangle = \delta_{ij} \}. \)

\[ U(n) = \{ A \in GL_n(\mathbb{C}) : AA^t = I \} \] – unitary group. Compact: \( A \in U(n) \) iff its columns are orthonormal.

Note: \( O(1) = \mathbb{Z}/2, SO(1) = 1, \) and \( O(2)/S^1 = \mathbb{Z}/2, SO(2) = S^1. \)

(e) \( SU(n) = \{ A \in U(n) : \det A = 1 \} = SL_n(\mathbb{C}) \cap U(n) \).

\[ SU(2) = \left\{ \left( \begin{array}{cc} z_1^2 & z_2^2 \\ \frac{1}{z_2^2} & \frac{1}{z_1^2} \end{array} \right) : z_i \in \mathbb{C}, |z_1|^2 + |z_2|^2 = 1 \right\} \] – spin group

\[ \cong S^3 = \{ z \in \mathbb{C}^2 : ||z|| = 1 \} \rightarrow \mathbb{C}^2 \cong \mathbb{R}^4 \] (homeomorphic).

\( SO(n) = \{ A \in O(n) : \det A = 1 \} = SL_n(\mathbb{R}) \cap O(n) \).

E.g., \( SO(2) \cong U(1), \) rotation of \( \theta \mapsto e^{i\theta} \)

\( SO(3), \) rotations about various axes in \( \mathbb{R}^3. \)

\( SO(n), SU(n), U(n), O(n) \) are groups of isometries of geometric objects – known as compact **Lie** groups. Theory is done by H. Weyl, ‘Classical Groups’.

(15.3) **Definition.** A **representation** of a topological group on a finite-dimensional vector space \( V \) is a continuous group homomorphism \( \rho : G \to GL(V) \) with the topology of \( GL(V) \) inherited from the space \( End V. \)

(There exist extensions when \( V \) is infinite-dimensional – see Telemann, remark 19.2.)

Here, continuous \( \rho : G \to GL(V) \cong GL_n(\mathbb{C}) \) means each \( g \mapsto (\rho(g))_{ij} \) is continuous for \( i,j \), or the map \( G \times V \to V, (g,v) \mapsto \rho(g)v \) is continuous.

The compact group \( U(1) \)

(15.4) **Theorem.** The continuous homomorphisms \( C^1 \to GL_1(\mathbb{C}) = \mathbb{C}^\times \) (i.e. the 1-dim. representations of \( S^1 \)) are precisely the representations \( z \mapsto z^n \) (some \( n \in \mathbb{Z} \)).

The proof is closely tied with Fourier Series. We need a couple of lemmas.

(15.5) **Lemma.** Consider \( (\mathbb{R},+) \). If \( \psi : \mathbb{R} \to \mathbb{R} \) is a continuous homomorphism then \( \psi \) is multiplication by a scalar. (I.e., solve \( \psi(x+y) = \psi(x) + \psi(y) \) for \( \psi \) a continuous function.)

**Proof.** Put \( c = \psi(1) \). Then \( \psi(n) = nc \) (\( n \in \mathbb{Z} \)). Also \( m\psi(1/m) = c, \) so \( \psi(1/m) = c/m \) (\( m \in \mathbb{Z} \)). Hence \( \psi(n/m) = cn/m. \) Thus \( \psi(x) = cx \) (\( x \in \mathbb{Q} \)), but \( \mathbb{Q} \) is dense in \( \mathbb{R} \) and \( \psi \) is continuous, so \( \psi(x) = cx \) for all \( x \in \mathbb{R}. \)

(15.6) **Lemma.** If \( \phi : \mathbb{R}^+ \to U(1) \) is a continuous homomorphism then there exists \( c \in \mathbb{R} \) with \( \phi(x) = e^{i cx} \) for all \( x \in \mathbb{R}. \)
Proof. Claim. There is a unique continuous homomorphism \( \alpha : \mathbb{R} \to \mathbb{R} \) such that \( \phi(x) = e^{i\alpha(x)} \) (so we deduce (15.6) from (15.5)).

Recall that the exponential map \( \varepsilon : \mathbb{R}^+ \to U(1), x \mapsto e^{ix} \), maps the real line around the unit circle with period \( 2\pi \).

![Diagram](Image)

For any continuous \( \phi : \mathbb{R}^+ \to U(1) \) such that \( \phi(0) = 1 \), there exists a unique continuous lifting \( \alpha \) of this function to the real line such that \( \alpha(0) = 0 \) – i.e., there exists a unique continuous \( \alpha : \mathbb{R} \to \mathbb{R} \) such that \( \alpha(0) = 0 \) and \( \phi(x) = \sum (\alpha(x)) \) for all \( x \).

(Lifting is constructed starting with condition \( \alpha(0) = 0 \) and then extending it a small interval at a time. See Telemann, section 21. Non-examinable!)

Claim. If \( \phi \) is a homomorphism then its lift \( \alpha \) is also a homomorphism. (So \( \alpha(x) = cx \), some \( c \) – (15.4).)

We tensor \( \phi(a + b) = \phi(a)\phi(b) \), hence \( \varepsilon (\alpha(a + b) - \alpha(a) - \alpha(b)) = 1 \). Hence \( \alpha(a + b) - \alpha(a) - \alpha(b) = 2\pi m \) for some \( m \in \mathbb{Z} \) depending only on \( a, b \). Varying \( a, b \) continuously, \( m = \) constant; setting \( a = b = 0 \) shows \( m = 0 \). \( \square \)

Proof of (15.4). Given a representation \( \rho : S^1 \to \mathbb{C}^\times \), it has a compact, hence bounded, image. This image lies on the unit circle (integral powers of any other complex number would form an unbounded sequence). Thus \( \rho : S^1 \to S^1 \) is a continuous homomorphism.

Thus we get a homomorphism \( \mathbb{R} \to S^1, x \mapsto \rho(e^{ix}) \), so by (15.6), there exists \( c \in \mathbb{R} \) with \( \rho(e^{ix}) = e^{icx} \).

Finally, \( 1 = \rho(e^{2\pi i}) = e^{2\pi c} \), thus \( c \in \mathbb{Z} \). Putting \( n = c \) we have \( \rho(z) = z^n \). \( \square \)

So \( \rho_n : U(1) \to \mathbb{C}^\times, z \mapsto z^n, (n \in \mathbb{Z}) \) give the complete list of irreducible representations of \( U(1) \).

Schur’s Lemma applies – all irreducibles are 1-dimensional (cf. (4.4.)). Clearly their characters are linearly independent; in fact they are orthonormal under the inner product

\[
\langle \phi, \psi \rangle = \frac{1}{2\pi} \int_0^{2\pi} \phi(\theta)\psi(\theta) d\theta \quad (\ast)
\]

where \( z = e^{i\theta} \). I.e., ‘averaging over \( U(1) \)’. Finite linear combinations of these \( \rho_n \) are the Fourier polynomials = \( \sum_{m=-n}^n a_m \rho_m \); the \( \rho_n \) are the Fourier modes.

\( U(1) \) is abelian, hence coincides with the space of conjugacy classes

**Theorem.** (i) The functions \( \rho_n \) form a complete list of the irreducible representations of \( U(1) \).

(ii) Every finite-dimensional representation \( V \) of \( U(1) \) is isomorphic to a sum of the \( \rho_n \). Its character \( \chi_V \) is a Fourier polynomial. The multiplicity of \( \rho_n \) in \( V \) equals \( \langle \rho_n, \chi_V \rangle \) (as in (\ast)).
Remark. Complete reducibility of a finite-dimensional representation requires invoking Weyl’s Unitary Trick (3.4′) to average over a given inner product using integration on $U(1)$—so before moving on to $SU(2)$, let’s consider a more general theory of compact groups.

General theory of compact groups

The main tools for studying representations of finite groups are:

- Schur’s Lemma – holds here too
- Maschke’s Theorem. The relevant proof used Weyl’s trick of averaging over $G$. Need to replace summation by integration over compact group $G$.

Namely, for each continuous function $f$ on $G$, we have $\int_G f(g) \, dg \in \mathbb{C}$ such that:

- $\int_G$ is a non-trivial linear functional
- $\int_G$ is left/right-invariant, i.e. $\int_G f(g) \, dg = \int_G f(hg) \, dg = \int_G f(gh) \, dg$ ($h \in G$)
- $G$ has total volume 1, i.e. $\int_G \, dg = 1$

A (difficult) theorem of Haar asserts that these constraints determine existence and uniqueness for any compact $G$. We’ll assume it, but for our Lie groups of interest ($U(1)$, $SU(2)$, etc) there are easier proofs of existence.

(15.8) Examples. 
(a) $G$ finite. $\int_G f(g) \, dg = \frac{1}{|G|} \sum_{g \in G} f(g)$.
(b) $G = S^1$. $\int_G f(g) \, dg = \frac{1}{2\pi} \int_0^{2\pi} f(e^{i\theta}) \, d\theta$.
(c) $G = SU(2)$, $2 \times 2$ $\mathbb{C}$-matrices preserving complex inner product and $\det = 1$.

Le, $SU(2) = \left\{ \begin{pmatrix} u & u \\ -\overline{u} & \overline{u} \end{pmatrix} : |u|^2 + |v|^2 = 1 \right\}$.

Identify $G$ with the unit 3-sphere $S^3 \subseteq \mathbb{C}^2 \cong \mathbb{R}^4$ in such a way that left/right translation by elements of $G$ give isometries on the sphere. With this identification, translation-invariant integration on $G$ can be taken to be integration over $S^3$ with usual Euclidean measure $\times 1/2\pi^2$ (to normalise).

(d) Embed $SU(2) \subseteq \mathbb{H} = \left\{ \begin{pmatrix} z_1 & z_2 \\ -\overline{z_2} & \overline{z_1} \end{pmatrix} : z_1, z_2 \in \mathbb{C} \right\}$, the quaternion algebra.

(Actually, it’s a division algebra, so that every non-zero element has an inverse.) $\mathbb{H}$ is a 4-dimensional Euclidean space: $||A|| = \sqrt{\det A} = (x_1^2 + x_2^2 + x_3^2 + x_4^2)^{1/2}$, where $z_1 = x_1 + ix_2$, $z_2 = x_3 + ix_4$, with $SU(2)$ as the unit sphere in this normed space.

Multiplication (from left or right) by an element of $SU(2)$ is an isometry of $\mathbb{H}$, viz:

$$(AX, AX) = \det AX = \det A \det X = \det X = (X, X) = (XA, XA),$$

where $A \in SU(2)$. 

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Once we have found our translation-invariant integration on the set of continuous functions on our compact group \( G \), a lot can be proved about the representation theory of \( G \) in parallel with finite groups.

Representations (continuous, finite-dimensional) \( \leadsto \) characters (continuous functions \( G \to \mathbb{C} \)).

Complete reducibility \( \leadsto \) Weyl’s Unitary Trick of averaging over \( G \) replaced by integration.

Character inner product: \( \langle \chi, \chi' \rangle = \int_G \overline{\chi(g)} \chi'(g) \, dg \) \((\dagger)\)

\( \chi \) irreducible iff \( \langle \chi, \chi \rangle = 1 \).

Moreover,

(15.9) \textbf{Theorem.} For \( G \) compact.

(a) Every finite-dimensional representation is a direct sum of irreducible representations (so completely reducible).

(b) Schur’s Lemma applies: if \( \rho, \rho' \) are irreducible representations of \( G \) then

\[
\text{Hom}(\rho, \rho') = \begin{cases} \mathbb{C} & \text{if } \rho \text{ is isomorphic to } \rho' \\ 0 & \text{otherwise} \end{cases}
\]

(c) The characters of irreducible representations form an orthonormal set with respect to the inner product (\( \dagger \)) above. (The set is infinite, and it is not a basis for the Hilbert space of all continuous class functions.)

Even showing completeness of characters is hard – needs Peter-Weyl Theorem.

(d) If the characters of \( \rho, \rho' \) are equal then \( \rho \cong \rho' \).

(e) If \( \chi \) is a character with \( \langle \chi, \chi \rangle = 1 \) then \( \chi \) is irreducible.

(f) If \( G \) is abelian then all irreducible representations are 1-dimensional.

\textbf{Note.} We don’t have actions on finite sets: the regular representation is infinite-dimensional.

\textbf{Comment.} The only spheres with continuous group homomorphisms are \( S^1 (= SO(2)) \) and the 3-sphere \( S^3 (= SU(3)) \).

\textbf{The group} \( SU(2) \)

Recall \( G = SU(2) = \left\{ \begin{pmatrix} a & b \\ -\bar{b} & \bar{a} \end{pmatrix} : a, b \in \mathbb{C}, |a|^2 + |b|^2 = 1 \right\} \).

\( G \to S^3 \hookrightarrow \mathbb{C}^2 = \mathbb{R}^4, \begin{pmatrix} a & b \\ -\bar{b} & \bar{a} \end{pmatrix} \mapsto (a_1, a_2, b_1, b_2). \) (Homeomorphism, i.e. continuous inverse.)

The centre is \( Z(G) = \{ \pm I \} \).

Define the \textbf{maximal torus} \( T = \left\{ \begin{pmatrix} a & 0 \\ 0 & \frac{1}{a} \end{pmatrix} : |a|^2 = 1 \right\} = S^1. \)
Conjugacy

(15.10) Proposition. (a) Every conjugacy class $C$ of $G = SU(2)$ meets $T$, i.e. $C \cap T \neq \emptyset$.

(b) In fact, $C \cap T = \begin{cases} \{x, x^{-1}\} & \text{if } C \neq \{\pm I\} \\ C & \text{if } C = \{\pm I\} \end{cases}$

(c) The normalised trace, $\frac{1}{2} tr : SU(2) \to \mathbb{C}$, gives a bijection of the set of $G$-conjugacy classes with the interval $[-1, 1]$, namely

$$g \in C \mapsto \frac{1}{2} tr = \frac{1}{2} \left( \lambda + \lambda^{-1} \right) \text{ if } g \sim \begin{pmatrix} \lambda & 0 \\ 0 & \lambda^{-1} \end{pmatrix}$$

Picture of ccls:

2-dim spheres of constant latitude on unit sphere, plus the two poles

Choose $x_1 = c$, then $x_2^2 + x_3^2 + x_4^2 = 1 - c^2$, so $-1 < c < 1$.

Given $c \in (-1, 1)$, all matrices $g \in G$ have $tr g = 2c$.

Proof. Let $S = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \in G$, $S^2 = -I$.

(a) Every unitary matrix has an orthonormal basis of eigenvectors, hence is conjugate in $U(2)$ to something in $T$, say $QXQ^t \in T$.

We seek $Q$ with $det Q = 1$ (so that $Q \in SU(2)$).

Let $\delta = det Q$. Since $QXQ^t = I$, $|\delta| = 1$. If $\varepsilon$ is a square root of $\delta$ then $Q_1 = \varepsilon Q \in SU(2)$ (since $\varepsilon = 1/\varepsilon$), hence $Q_1XQ_1^t \in T$.

(b) Let $g \in SU(2)$ and suppose $g \in C_G$. If $g = \pm I$ then $C \cap T = \{g\}$.

Otherwise $g$ has distinct eigenvalues $\lambda, \lambda^{-1}$ and $C = \left\{ h \begin{pmatrix} \lambda & 0 \\ 0 & \lambda^{-1} \end{pmatrix} h^{-1} : h \in G \right\}$.

Thus $C \cap T = \left\{ \begin{pmatrix} \lambda & 0 \\ 0 & \lambda^{-1} \end{pmatrix}, \begin{pmatrix} \lambda^{-1} & 0 \\ 0 & \lambda \end{pmatrix} \right\}$, by noting $S \begin{pmatrix} \lambda & 0 \\ 0 & \lambda^{-1} \end{pmatrix} S = \begin{pmatrix} \lambda^{-1} & 0 \\ 0 & \lambda \end{pmatrix}$.

Further, if $\begin{pmatrix} \mu & \mu^{-1} \end{pmatrix} \in C$ then $\{\mu, \mu^{-1}\} = \{\lambda, \lambda^{-1}\}$, i.e. the eigenvalues are preserved under conjugacy.

(c) Consider $\frac{1}{2} tr : \{ccls\} \to [-1, 1]$. By (b) matrices are conjugate in $G$ iff their eigenvalues agree up to order. Now

$$\frac{1}{2} tr \left( \begin{pmatrix} \lambda & 0 \\ 0 & \lambda^{-1} \end{pmatrix} \right) = \frac{1}{2} (\lambda + \lambda^{-1}) = Re(\lambda) = cos \theta \ (\lambda = e^{i\theta})$$

hence the map is surjective onto $[-1, 1]$.

It’s injective: $\frac{1}{2} tr (g) = \frac{1}{2} tr (g')$ then $g, g'$ have the same characteristic polynomial, viz $X^2 - tr(g)X + 1$, hence the same eigenvalues, hence are conjugate. \[\square\]

Thus we write $C_t = \{ g \in SU(2) : \frac{1}{2} tr (g) = t \}$. 50
Representations

Let $V_n$ be the space of all homogeneous polynomials of degree $n$ in the variables $x, y$.

I.e., $V_n = \{ r_0 x^n + r_1 x^{n-1} y + \ldots + r_n y^n \}$, an $(n + 1)$-dimensional $\mathbb{C}$-space, with basis $x^n, x^{n-1}y, \ldots, y^n$.

\[(15.11)\] $GL_2(\mathbb{C})$ acts on $V_n$.

First, define $\rho_n : GL_2(\mathbb{C}) \rightarrow GL(V_n) \cong GL_{n+1}(\mathbb{C})$. Let $g = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$.

$\rho_n(g)f(x, y) = f(ax + cy, bx + dy) = f((x, y)g)$ (i.e., matrix product)

I.e., for $f = \sum_{j=0}^n r_j x^{n-j} y^j$, $\rho(g)f = r_0(ax + cy)^n + r_1(ax + cy)^{n-1}(bx + dy) + \ldots + r_n(bx + dy)^n$.

Check that this defines a representation.

E.g. (a) $n = 0$, $\rho_0 =$ trivial

(b) $n = 1$, natural 2-dimensional representation. $\rho_1 \begin{pmatrix} a & b \\ c & d \end{pmatrix}$ has matrix $\begin{pmatrix} a & b \\ c & d \end{pmatrix}$ with respect to the standard basis: $x \mapsto ax + cy, y \mapsto bx + dy$.

(c) $n = 2$, $\rho_2 = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$ has matrix $\begin{pmatrix} a^2 & cb & b^2 \\ 2ac & ad + bc & 2bd \\ c^2 & cd & d^2 \end{pmatrix}$ with respect to the standard basis.

(We have $(ax + cy)^2 + (ax + cy)(bx + dy) + (bx + dy)^2$, so the first column is the coordinate vector of $\rho_2(g)x^2 = (ax + cy)^2 = a^2x^2 + 2acxy + c^2y^2$.)

Characters

$\chi_{V_n}(g) = \text{tr}(\rho_n(g)), \ g \sim \begin{pmatrix} z & \\ z^{-1} \end{pmatrix} \in T$.

$\rho_n \begin{pmatrix} z & \\ z^{-1} \end{pmatrix} x^iy^j = (zx)^i(z^{-1}y)^j = z^{i-j}x^iy^j$.

So $\rho_n \begin{pmatrix} z & \\ z^{-1} \end{pmatrix}$ has matrix $\begin{pmatrix} z^n & z^{n-2} & \ldots & \vdots \\ & & \ddots & \vdots \\ & & & z^{-n} \end{pmatrix}$ with respect to the standard basis.

Hence, $\chi_n = \chi_{V_n} \begin{pmatrix} z & \\ z^{-1} \end{pmatrix} = z^n + z^{n-2} + \ldots + z^{-n} \begin{pmatrix} z^{n+1} - z^{-(n+1)} \\ z - z^{-1} \end{pmatrix} = 0$ unless $z = \pm 1$.

\[(15.12)\] Theorem. The representations $\rho_n : SU(2) \rightarrow GL(V_n)$ of dimension $n + 1$ are irreducible for $n \in \mathbb{Z}_{\geq 0}$.

Proof. Telemann (21.1) shows $\langle \chi_n, \chi_n \rangle = 1$ (implying $\chi_n$ irreducible, by (15.9)(e)). We will use combinatorics. Assume $0 \neq W \subseteq V_n$, $G$-invariant.

Claim. If $w = \sum_j r_j x^{n-j} y^j \in W$ with some $r_j \neq 0$, then $x^{n-j} y^j \in W$.
Proof of claim. We argue by induction on the number of non-zero $r_j$. If a unique $r_j \neq 0$ then it’s clear (multiply by its inverse), so we’ll assume more than one and choose one.

Pick $z \in \mathbb{C}$ with $z^n, z^{n-2}, \ldots, z^{-n}$ distinct in $\mathbb{C}$.

Now, $\rho_n \left( \frac{z}{z^{-1}} \right) w = \sum r_j z^{n-2j} x^{n-j} y^j \in W$ (G-space).

Define $w_i = \rho_n \left( \frac{z}{z^{-1}} \right) w - z^{n-2i} w \in W$.

Then $w_i = \sum_j r'_j x^{n-j} y^j$ and $r'_j \neq 0 \Leftrightarrow (r_j \neq 0$ and $j \neq i)$. By induction hypothesis, we have $x^{n-j} y^j \in W$ for all $j$ with $(r_j \neq 0$ and $j \neq i)$.

Finally, $x^{n-i} y^i = r_i^{-1} (w - \sum_j r_j x^{n-j} y^j) \in W$, so the claim is proved.

Now let $0 \neq w \in W$. Wlog, $w = x^{n-j} y^j$. It is now easy to find matrices in $SU(2)$, the action of which will give all the $x^{n-i} y^i \in W$.

E.g.,

$$\frac{1}{\sqrt{2}} \begin{pmatrix} 1 & -1 \\ 1 & 1 \end{pmatrix} : x^{n-i} y^i \mapsto \frac{1}{\sqrt{2}} (x + y)^{n-i} (-x + y)^i \rightarrow x^n \in W$$

$$\begin{pmatrix} a & -b \\ b & a \end{pmatrix} : x^n \mapsto (ax + by)^n \rightarrow \text{all } x^{n-i} y^i \in W$$

(a, b ≠ 0) all coefficients in here ≠ 0

So all basis elements are in $W$. So $W = V_n$. □

Next we show that all irreducibles of $SU(2)$ are of the form in (15.12).

Notation. Write $\mathbb{N}_0[z, z^{-1}] = \left\{ \sum_{m=-n}^n a_m z^m : a_m \in \mathbb{N}_0 \right\}$.

And $\mathbb{N}_0[z, z^{-1}]_{ev} = \{ \text{even Laurent polynomials, i.e. } a_m = a_{-m} \text{ for all odd } m \}$.

Let $\chi = \chi_V$ be the character of some representation $\rho : G \rightarrow GL(V)$. If $g \in G = SU(2)$ then $g \sim_G \begin{pmatrix} z & \ast \\ \ast & z^{-1} \end{pmatrix}$ for some $z \in \mathbb{C}$. So $\chi_V$ is determined by its restriction to $T$, hence $\chi_V \in \mathbb{N}_0[z, z^{-1}]$ by (1).

Actually $\chi_V \in \mathbb{N}_0[z, z^{-1}]_{ev}$, as $\chi_V \begin{pmatrix} z & \ast \\ \ast & z^{-1} \end{pmatrix} = \chi_V \begin{pmatrix} z & \ast \\ \ast & z^{-1} \end{pmatrix}$, because $\begin{pmatrix} z & \ast \\ \ast & z^{-1} \end{pmatrix} \sim_G \begin{pmatrix} z & \ast \\ \ast & z^{-1} \end{pmatrix}$ via $S = \begin{pmatrix} -1 & 1 \\ \ast & \ast \end{pmatrix}^{-1}$.

(15.13) Theorem. Every (finite-dimensional, continuous) irreducible representation of $G$ is one of the $\rho_n : G \rightarrow GL(V_n)$ above $(n \geq 0)$.

Proof. Assume $\rho : G \rightarrow GL(V)$ is an irreducible representation affording the character $\chi$.

The characters characterise representations (15.9)(d), so it’s enough to show $\chi = \chi_n$ for some $n$. 

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Now $\chi_0 = 1$, $\chi_1 = z + z^{-1}$, $\chi_2 = z^2 + 1 + z^{-2}$, \ldots form a basis of $Q[z, z^{-1}]_{ev}$, hence $\chi = \sum a_n \chi_n$, a finite sum with $a_n \in \mathbb{Q}$.

Clear the denominators and move all summands with negative coefficients to the LHS:

$$m\chi + \sum_{i \in I} m_i \chi_i = \sum_{j \in J} n_j \chi_j$$

with $I, J$ disjoint finite subsets of $\mathbb{N}$, and $m, m_i, n_j \in \mathbb{N}$.

The left and right hand sides are characters of representations of $SU(2)$:

$$mV \oplus \bigoplus_{I} m_i V_i \cong \bigoplus_{J} n_j V_j.$$

Since $V$ is irreducible we must have $V \cong V_n$, for some $n \in J$. □

So we have found all irreducible representations of $G$; they are $\rho_n : G \to GL(V_n)$ ($n \neq 0$) with $V_n$ the $(n+1)$-dimensional space of homogeneous polynomials of degree $n$ in $x, y$. The characters of $\rho_n$ are given by $(\dagger)$.

To compute representations we ‘just’ work with characters: as an example we derive a famous rule for decomposing tensor products.

**Tensor product of representations**

Recall from section 9: if $V, W$ are $G$-spaces we have $V \otimes W$ affording $\chi_{V \otimes W} = \chi_V \chi_W$.

**Examples.** $V_1 \otimes V_1 = V_2 \oplus V_0$.

Character $= (z + z^{-1})^2 = z^2 + 2 + z^{-2} = (\underbrace{z^2 + 1 + z^{-2}}_{V_2}) + 1_{V_0}$

$V_1 \otimes V_2 = V_3 \oplus V_1$.

Character $= (z + z^{-1})(z^2 + 1 + z^{-2}) = (z^3 + z + z^{-1} + z^{-3}) + (z + z^{-1})$

(15.14) **Theorem (Clebsch-Gordan).** $V_n \otimes V_m = V_{n+m} \oplus V_{n+m-2} \oplus \ldots \oplus V_{|n-m|}$

**Proof.** Just check that the characters work.

Wlog $n \geq m$ and prove $\chi_n \chi_m = \chi_{n+m} + \chi_{n+m-2} + \ldots + \chi_{n-m}$.

$$\chi_n(g) \chi_m(g)$$

$$= \frac{z^{n+1} - z^{-n-1}}{z - z^{-1}} (z^m + z^{m-2} + \ldots + z^{-m})$$

$$= \sum_{j=0}^{m} \frac{z^{n+m+1-2j} - z^{2j-n-m-1}}{z - z^{-1}}$$

$$= \sum_{j=0}^{m} \chi_{n+m-2j}$$

(The $n \geq m$ ensures no cancellations in the sum.) □

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Some $SU(2)$-related groups

Check (see Telemann 22.1, and Examples Sheet 4 Question 6):

- $SO(3) \cong SU(2)/\{\pm I\}$
- $SO(4) \cong SU(2) \times SU(2)/\{\pm (I, I)\}$
- $U(2) \cong U(1) \times SU(2)/\{\pm (I, I)\}$

(Isomorphisms, but actually homeomorphisms.)

So continuous representations of these groups are the same as continuous representations of $SU(2)$ and $SU(2) \times SU(2)$, respectively, which send $-I$ and $(-I, -I)$ to the identity matrix.

(15.15) Corollary. The irreducible representations of $SO(3)$ are precisely $\rho_{2m} : SO(3) \to GL(V_{2m})$ ($m \geq 0$).

Remarks. (a) We get precisely those $V_n$ with $-\text{id}$ in the kernel of the action, and $-\text{id}$ acts on $V_n$ as
\[
\begin{pmatrix}
(-1)^n & 0 & \ldots & 0 \\
0 & (-1)^{n-2} & \ldots & 0 \\
\vdots & \ddots & \ddots & \vdots \\
0 & \ldots & 0 & (-1)^{-n}
\end{pmatrix}
=(-1)^n \text{id}
\]

(b) $V_2$ is the standard 3-dimensional representation of $SO(3)$. (The only 3-dimensional representation in the list.)

(c*) For $SO(4)$ the complete list is $\rho_m \otimes \rho_n$ ($m, n \geq 0$, $m \equiv n(2)$) (see Telemann 22.7).
For $U(2)$ the list is $\det \otimes \rho_m \otimes \rho_n$ ($m, n \in \mathbb{Z}$, $n \geq 0$) where $\det : U(2) \to U(1)$ is 1-dimensional (see Telemann 22.9).

Sketch proof of (c*) Recall from (15.8)(d) that $SU(2) \subseteq \mathbb{H} \cong \mathbb{R}^4$ can be viewed as the space of unit norm quaternions. We also saw that multiplication from the left (and right) by elements of $SU(2)$ gives isometries of $\mathbb{H}$. The left/right multiplication action of $SU(2)$ gives a homomorphism $\phi : SU(2) \times SU(2) \to SO(4)$, $(g, h) \mapsto \{\theta : q \mapsto gh^{-1}\}$.

Kernel. $(g, h)$ sends $1 \in \mathbb{H}$ to $gh^{-1}$, so $(g, h)$ fixes the identity iff $g = h$, i.e. $G = \{(g, g) : g \in SU(2)\} = \text{stab}_{SU(2) \times SU(2)}(1)$.

Now $(g, g)$ fixes every other quaternion iff $g \in Z(SU(2))$, i.e. $g = \pm \text{id}$. Thus $\ker \phi = \{\pm (I, I)\}$.

Surjective and homeomorphic (i.e. inverse map is continuous). Restricting the left/right action to $G$ (the diagonal embedding of $SU(2)$) give the conjugation action of $SU(2)$ on the space of ‘pure quaternions’, $\langle i, j, k \rangle_{\mathbb{R}}$ (the trace 0 skew-Hermitian $2 \times 2$ matrices). So get a 3-dimensional Euclidean space on which $G$ acts, and $\phi(G) \leq SO(3)$.

$\phi(G) = SO(3)$. Rotations in $\langle i, j \rangle$-plane implemented by $a + bk$, similarly with any permutations of $i, j, k$, and these rotations generate $SO(3)$ (see some Geometry course). So we have a surjective homomorphism $SU(2) \to SO(3)$, and we know that $\ker = \{\pm \text{id}\}$. The result follows.

Homeomorphism. Prove it directly or ‘recall’ the fact that a continuous bijection from a compact space to a Hausdorff space is a homeomorphism (Sutherland 5.9.1)
Further worked example

$S_n$, $GL_2(\mathbb{F}_q)$, $H_p$.

We consider Heisenberg groups. For $p$ prime, the abelian groups of order $p^3$ are $C_{p^3}$, $C_{p^2} \times C_p$, $C_p \times C_p \times C_p$, and their character tables can be constructed using (4.5).

Suppose $G$ is any non-abelian group of order $p^3$. Let $Z = Z(G)$, then it’s well-known that $Z \neq 1$ and $G/Z$ is non-cyclic, i.e. $G/Z \cong C_p \times C_p$ and $Z = C_p$.

Take $G = H_p = \{ \begin{pmatrix} 1 & * & * \\ 0 & 1 & * \\ 0 & 0 & 1 \end{pmatrix} : * \in \mathbb{F}_p \}$, the modular Heisenberg group.

We take $p$ odd (else $G = D_8$ or $Q_8$).

Have $Z = \langle z \rangle$, $z = \begin{pmatrix} 1 & 0 & 1 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$.

With $a = \begin{pmatrix} 1 & 1 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$ and $b = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 0 & 1 \end{pmatrix}$, $[a, b] = z$ and $G' = Z$.

There are $p^2$ linear characters (of degree 1) (recall $G/G' = C_p \times C_p$), and $(p - 1)$ characters of degree $p$, induced from the 1-dimensional characters of the abelian subgroup

$$\langle a, z \rangle = \{ \begin{pmatrix} 1 & * & * \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \}$$

of order $p^2$.

Conjugacy classes

$p$ conjugacy classes of size 1. The rest have size $p$ and there are $p^2 - 1$ such classes.

We’ll show that the character table of $H_p$ looks like

\[
\begin{array}{cccccccc}
1 & z & \cdots & z^{p-1} & a & ab & \cdots & a^{-1}b^{-1} \\
p^2 \text{ linear} & & & & & & & \text{central ccls} \\
\text{characters} & & & & & & & \text{central ccls} \\
p - 1 \text{ characters} & & & & & & \text{of degree } p \\
\text{of degree } p & & & & & & \text{of degree } p \\
p & p\omega & \cdots & \cdots & p & \times \text{char.} & \cdots & \text{of degree } C_p \\
\text{of degree } p & & & & & & \text{of degree } p & \text{char. table of } C_p \\
\end{array}
\]

0
More formally,

- $Z = \langle z \rangle$ gives $p$ conjugacy classes of size 1: $\{1\}, \{z\}, \ldots, \{z^{p-1}\}$.
- $G/Z = (aZ, bZ) = \{a^i b^j z^k : 0 \leq i \leq p - 1, 0 \leq j \leq p - 1\}$. So, in particular, every element of $G$ is of the form $a^i b^j z^k$, $0 \leq i, j, k \leq p - 1$.
- the $p^2 - 1$ conjugacy classes of size $p$ are $C(a^i b^j) = \{a^i b^j z^k : 0 \leq k \leq p - 1, (i, j) \neq (0, 0)\}$.

For $aba^{-1}b^{-1} = z : aba^{-1} = zb$ (as $b = z$ central)

$bab^{-1} = az^{-1}$

$⇒ aa^i b^j a^{-1} = a^i (a b^{-1}) = a^i b^{-1} z^j$.

$b a^i b^{-1} = (a b^{-1}) b^j = a^i b^j z^{-i}$

I.e., any conjugate of $a^i b^j$ is some $a^i b^j z^k$, as above.

Irreducible characters

(15.16) Theorem. As above, let $G = \{a^i b^j z^k : 0 \leq i, j, k \leq p - 1\}$ be a non-abelian group of order $p^3$. Write $\omega = e^{2\pi i/p} \in \mu_p$. Then the irreducible characters of $G$ are:

$$\chi_{u,v}(0 \leq u, v \leq p - 1) \quad (p^2 \text{ of degree } 1)$$

$$\phi_u(1 \leq u \leq p - 1) \quad (p^2 - 1 \text{ of degree } p)$$

where for all $i, j, k$,

$$\chi_{u,v}(a^i b^j z^k) = w^{iu + jv}$$

$$\phi_u(a^i b^j z^k) = \begin{cases} p \omega^{uk} & \text{if } i = j = 0 \\ 0 & \text{otherwise} \end{cases}$$

Proof. First, the $p^2$ linear characters. The irreducible characters of $G^{ab} = G/G' = G/Z = C_p \times C_p$ are $\psi_{u,v}(a^i b^j Z) = \omega^{iu + jv} (0 \leq u, v \leq p - 1)$. The lift to $G$ of $\psi_{u,v}$ is precisely $\chi_{u,v}$.

Next, the $p - 1$ characters of degree $p$.

Now, $H = \begin{cases} 1 & * & * \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{cases} \in \langle a, z \rangle$ is a normal abelian subgroup of index $p$.

Let $\psi_u$ be a character of $H$ defined as $\psi_u(a^i z^k) = \omega^{uk} (0 \leq k \leq p - 1)$, and calculate $\psi^G_u$. Choose transversal $\{1, b, \ldots, b^{p-1}\}$ of $H$ in $G$.

$$\psi^G_u(a^i z^k) = \psi_u(a^i) + \psi_u(a^i z) + \ldots + \psi_u(a^i z^{p-1})$$

$$= \psi_u(a^i) \sum_{r=0}^{p-1} \omega^{ur} \quad \text{(as homomorphic)}$$

$$= \psi_u(a^i) \sum_{r=0}^{p-1} \omega^{ur} = 0$$

$$\psi^G_u(z^k) = \sum_j \tilde{\psi}_u(b^j z^k b^{-j}) = p \psi_u(z^k) = p \omega^{uk},$$

and $\psi_u(g) = 0$ for all $g \notin H$.

Thus $\psi^G_u = \phi_u$. 

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Finally,

$$\langle \phi_n, \phi_n \rangle = \frac{1}{p^3} \sum_{g \in G} \phi_u(g)\phi_u(g) = \frac{1}{p^3} \sum_{g \in Z} \phi_u(g)\phi_u(g)$$

$$= \frac{1}{p^3} \sum_{k=0}^{p-1} \phi_u(z^k)\phi_u(z^k) = \frac{1}{p^3} \sum z^2 = 1$$

Remarks. 1. Alternative is to apply Mackey (12.6).

2. Typically for $p$-groups: any irreducible representation is induced from a 1-dimensional representation of some subgroup (Telemann, chapter 17).

3. For $p$ odd, in fact there are two non-abelian groups of order $p^3$:

   $$G_1 = \langle a, b : a^{p^2} = b^p = 1, b^{-1}ab = a^{p+1} \rangle \text{ with } Z = \langle a^p \rangle$$

   $$G_2 = \langle a, b, z : a^p = b^p = z^p = 1, az = za, bz = zb, b^{-1}ab = az \rangle \text{ with } Z = \langle z \rangle$$
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. Let $\rho$ be a representation of the group $G$.
   (a) Show that $\delta : g \mapsto \det \rho(g)$ is a 1-dimensional representation of $G$.
   (b) Prove that $G/\ker \delta$ is abelian.
   (c) Assume that $\delta(g) = -1$ for some $g \in G$. Show that $G$ has a normal subgroup of index 2.

2. Let $\theta : G \to F^\times$ be a 1-dimensional representation of the group $G$, and let $\rho : G \to \text{GL}(V)$ be another representation. Show that $\theta \otimes \rho : G \to \text{GL}(V)$ given by $\theta \otimes \rho : g \mapsto \theta(g) \cdot \rho(g)$ is a representation of $G$, and that it is irreducible if and only if $\rho$ is irreducible.

3. Let $G$ be the alternating group $A_4$. Find all the degree one representations of $G$ over $F$ for:
   (a) $F = \mathbb{C}$;
   (b) $F = \mathbb{R}$;
   (c) $F = \mathbb{Z}/3\mathbb{Z}$.
   [Hint: you can use the fact that the Klein 4-group $V = \{1, (1,2)(3,4), (1,3)(2,4), (1,4)(2,3)\}$ is the unique normal subgroup of $A_4$ (apart from the trivial subgroup and $A_4$ itself)].

   Now let $G = D_{12}$, the symmetry group of a regular hexagon. Let $a \in G$ be a rotation through $\pi/3$ anticlockwise, and let $b \in G$ be a reflection, so that $G = \{a^i, a^ib^j : 0 \leq i \leq 5\}$. Let $A, B, C, D \in \text{GL}_2(\mathbb{C})$ be the matrices
   \[
   A = \begin{pmatrix} e^{\pi i/3} & 0 \\ 0 & e^{-\pi i/3} \end{pmatrix}, \quad B = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad C = \begin{pmatrix} 1 & \sqrt{3} \\ \frac{1}{2} & \frac{1}{2} \end{pmatrix}, \quad D = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}.
   \]
   Each of the following is a (matrix) representation of $G$ over $\mathbb{C}$ (you need not verify this):
   \[
   \begin{align*}
   \rho_1 : a^ib^j & \mapsto A^i B^j, \\
   \rho_2 : a^ib^j & \mapsto A^{3i}(-B)^j, \\
   \rho_3 : a^ib^j & \mapsto (-A)^i B^j, \\
   \rho_4 : a^ib^j & \mapsto C^i D^j.
   \end{align*}
   \]
   Which of these are faithful? Which are equivalent to one another?

4. (Counterexamples to Maschke’s Theorem)
   (a) Let $FG$ denote the regular $FG$-module (i.e. the permutation module coming from the action of $G$ on itself by left multiplication), and let $F$ be the trivial module. Find all the $FG$-homomorphisms from $FG$ to $F$ and vice versa. By considering a submodule of $FG$ isomorphic to $F$, prove that whenever the characteristic of $F$ divides the order of $G$, there is a counterexample to Maschke’s Theorem.

   (b) Find an example of a representation of some finite group over some field of characteristic $p$, which is not completely reducible. Find an example of such a representation in characteristic 0 for an infinite group.
5 Let $N$ be a normal subgroup of the group $G$. Given a representation of the quotient $G/N$, use it to obtain a representation of $G$. Which representations of $G$ do you get this way?

Recall that the derived subgroup $G'$ of $G$ is the unique smallest normal subgroup of $G$ such that $G/G'$ is abelian. Show that the 1-dimensional complex representations of $G$ are precisely those obtained from $G/G'$.

6 Let $G$ be a cyclic group of order $n$. Decompose the regular representation of $G$ explicitly as a direct sum of 1-dimensional representations, by giving the matrix of change of coordinates from the natural basis $\{e_g\}_{g \in G}$ to a basis where the group action is diagonal.

7 Let $G$ be the dihedral group $D_{10}$ of order 10,

$$D_{10} = \langle x, y : x^5 = 1 = y^2, yxy^{-1} = x^{-1} \rangle.$$

Show that $G$ has precisely two 1-dimensional representations. By considering the effect of $y$ on an eigenvector of $x$ show that any complex irreducible representation of $G$ of dimension at least 2 is isomorphic to one of two representations of dimension 2. Show that all these representations can be realised over $\mathbb{R}$.

8 Let $G$ be the quaternion group $Q_8$ of order 8,

$$Q_8 = \langle x, y | x^4 = 1, y^2 = x^2, yxy^{-1} = x^{-1} \rangle.$$

By considering the effect of $y$ on an eigenvector of $x$ show that any complex irreducible representation of $G$ of dimension at least 2 is isomorphic to the standard representation of $Q_8$ of dimension 2.

Show that this 2-dimensional representation cannot be realised over $\mathbb{R}$; that is, $Q_8$ is not a subgroup of $\text{GL}_2(\mathbb{R})$.

9 State Schur’s lemma.

Show that if $G$ is a finite group with trivial centre and $H$ is a subgroup of $G$ with non-trivial centre, then any faithful representation of $G$ is reducible on restriction to $H$.

10 Let $G$ be a subgroup of order 18 of the symmetric group $S_6$ given by

$$G = \langle (123), (456), (23)(56) \rangle.$$

Show that $G$ has a normal subgroup of order 9 and four normal subgroups of order 3. By considering quotients, show that $G$ has two representations of degree 1 and four inequivalent irreducible representations of degree 2. Deduce that $G$ has no faithful irreducible representations.
11. In this question work over the field $F = \mathbb{R}$.
Let $G$ be the cyclic group of order 3.
(a) Write the regular $\mathbb{R}G$-module as a direct sum of irreducible submodules.
(b) Find all the $\mathbb{R}G$-homomorphisms between the irreducible $\mathbb{R}G$-modules.
(c) Show that the conclusion of Schur’s Lemma (‘every homomorphism from an irreducible module to itself is a scalar multiple of the identity’) is false if you replace $\mathbb{C}$ by $\mathbb{R}$.

From now on let $G$ be a cyclic group of order $n$. Show that:
(d) If $n$ is even, the regular $\mathbb{R}G$-module is a direct sum of two (non-isomorphic) 1-dimensional irreducible submodules and $(n-2)/2$ (non-isomorphic) 2-dimensional irreducible submodules.
(e) If $n$ is odd, the regular $\mathbb{R}G$-module is a direct sum of one 1-dimensional irreducible submodule and $(n-1)/2$ (non-isomorphic) 2-dimensional irreducible submodules.
[Hint: use the fact that $\mathbb{R}G \subset \mathbb{C}G$ and what you know about the regular $\mathbb{C}G$-module from question 6.]

12. Show that if $\rho$ is a homomorphism from the finite group $G$ to $\text{GL}_n(\mathbb{R})$, then there is a matrix $P \in \text{GL}_n(\mathbb{R})$ such that $P \rho(g) P^{-1}$ is an orthogonal matrix for each $g \in G$. (Recall that the real matrix $A$ is orthogonal if $A^tA = I$.)

Determine all finite groups which have a faithful 2-dimensional representation over $\mathbb{R}$.

SM, Lent Term 2011
Comments on and corrections to this sheet may be emailed to sm@dpmms.cam.ac.uk
Unless otherwise stated, all groups here are finite, and all vector spaces are finite-dimensional over a field $\mathbb{F}$ of characteristic zero, usually $\mathbb{C}$.

1. Let $\rho : G \to \text{GL}(V)$ be a representation of $G$ of dimension $d$, and affording character $\chi$. Show that $\ker \rho = \{ g \in G \mid \chi(g) = d \}$. Show further that $|\chi(g)| \leq d$ for all $g \in G$, with equality only if $\rho(g) = \lambda I$, a scalar multiple of the identity, for some root of unity $\lambda$.

2. Let $\chi$ be the character of a representation $V$ of $G$ and let $g$ be an element of $G$. If $g$ is an involution (i.e. $g^2 = 1 \neq g$), show that $\chi(g)$ is an integer and $\chi(g) \equiv \chi(1) \mod 2$. If $G$ is simple (but not $C_2$), show that in fact $\chi(g) \equiv \chi(1) \mod 4$. (Hint: consider the determinant of $g$ acting on $V$.) If $g$ has order 3 and is conjugate to $g^{-1}$, show that $\chi(g) \equiv \chi(1) \mod 3$.

3. Construct the character table of the dihedral group $D_8$ and of the quaternion group $Q_8$. You should notice something interesting.

4. Construct the character table of the dihedral group $D_{10}$.
   Each irreducible representation of $D_{10}$ may be regarded as a representation of the cyclic subgroup $C_5$. Determine how each irreducible representation of $D_{10}$ decomposes into irreducible representations of $C_5$.
   Repeat for $D_{12} \cong S_3 \times C_2$ and the cyclic subgroup $C_6$ of $D_{12}$.

5. Construct the character tables of $A_4$, $S_4$, $S_5$, and $A_5$.
   The group $S_n$ acts by conjugation on the set of elements of $A_n$. This induces an action on the set of conjugacy classes and on the set of irreducible characters of $A_n$. Describe the actions in the cases where $n = 4$ and $n = 5$.

6. The group $M_9$ is a certain subgroup of the symmetric group $S_9$ generated by the two elements $(1, 4, 9, 8)(2, 5, 3, 6)$ and $(1, 6, 5, 2)(3, 7, 9, 8)$. You are given the following facts about $M_9$:
   - there are six conjugacy classes:
     - $C_1$ contains the identity.
     - For $2 \leq i \leq 4$, $|C_i| = 18$ and $C_i$ contains $g_i$, where $g_2 = (2, 3, 8, 6)(4, 7, 5, 9)$, $g_3 = (2, 4, 8, 5)(3, 9, 6, 7)$ and $g_4 = (2, 7, 8, 9)(3, 4, 6, 5)$.
     - $|C_5| = 9$, and $C_5$ contains $g_5 = (2, 8)(3, 6)(4, 5)(7, 9)$
     - $|C_6| = 8$, and $C_6$ contains $g_6 = (1, 2, 8)(3, 9, 4)(5, 7, 6)$.
   - every element of $M_9$ is conjugate to its inverse.
   Calculate the character table of $M_9$. [Hint: You may find it helpful to notice that $g_2^2 = g_3^2 = g_4^2 = g_5$.]


7 A certain group of order 720 has 11 conjugacy classes. Two representations of this group are known and have corresponding characters $\alpha$ and $\beta$. The table below gives the sizes of the conjugacy classes and the values which $\alpha$ and $\beta$ take on them.

<table>
<thead>
<tr>
<th>Conjugacy Class Sizes</th>
<th>$\alpha$ Values</th>
<th>$\beta$ Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 15 40 90 45 120 144 120 90 15 40</td>
<td>6 2 0 0 2 2 1 1 0 -2 3</td>
<td>21 1 -3 -1 1 1 1 0 -1 -3 0</td>
</tr>
</tbody>
</table>

Prove that the group has an irreducible representation of degree 16 and write down the corresponding character on the conjugacy classes.

8 The table below is a part of the character table of a certain finite group, with some of the rows missing. The columns are labelled by the sizes of the conjugacy classes, and $\gamma = (-1 + i\sqrt{7})/2$, $\zeta = (-1 + i\sqrt{3})/2$. Complete the character table. Describe the group in terms of generators and relations.

<table>
<thead>
<tr>
<th>Character</th>
<th>1 3 3 7 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi_1$</td>
<td>1 1 1 $\zeta$ $\bar{\zeta}$</td>
</tr>
<tr>
<td>$\chi_2$</td>
<td>3 $\gamma$ $\bar{\gamma}$ 0 0</td>
</tr>
<tr>
<td>$\chi_3$</td>
<td>3 $\bar{\gamma}$ $\gamma$ 0 0</td>
</tr>
</tbody>
</table>

9 Let $x$ be an element of order $n$ in a finite group $G$. Say, without detailed proof, why

(a) if $\chi$ is a character of $G$, then $\chi(x)$ is a sum of $n$th roots of unity;
(b) $\tau(x)$ is real for every character $\tau$ of $G$ if and only if $x$ is conjugate to $x^{-1}$;
(c) $x$ and $x^{-1}$ have the same number of conjugates in $G$.

Prove that the number of irreducible characters of $G$ which take only real values (so-called real characters) is equal to the number of self-inverse conjugacy classes (so-called real classes).

A group of order 168 has 6 conjugacy classes. Three representations of this group are known and have corresponding characters $\alpha$, $\beta$ and $\gamma$. The table below gives the sizes of the conjugacy classes and the values $\alpha$, $\beta$ and $\gamma$ take on them.

<table>
<thead>
<tr>
<th>Conjugacy Class Sizes</th>
<th>$\alpha$ Values</th>
<th>$\beta$ Values</th>
<th>$\gamma$ Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 21 42 56 24 24</td>
<td>14 2 0 -1 0 0</td>
<td>15 -1 -1 0 1 1</td>
<td>16 0 0 -2 2 2</td>
</tr>
</tbody>
</table>

Construct the character table of the group.

[You may assume, if needed, the fact that $\sqrt{7}$ is not in the field $\mathbb{Q}(\zeta)$, where $\zeta$ is a primitive 7th root of unity.]

10 Let a finite group $G$ act on itself by conjugation. Find the character of the corresponding permutation representation.

11 Consider the character table $Z$ of $G$ as a matrix of complex numbers (as we did when deriving the column orthogonality relations from the row orthogonality relations).

(a) Using the fact that the complex conjugate of an irreducible character is also an irreducible character, show that the determinant $\det Z$ is $\pm \det \bar{Z}$, where $\bar{Z}$ is the complex conjugate of $Z$.

(b) Deduce that either $\det Z \in \mathbb{R}$ or $i \cdot \det Z \in \mathbb{R}$.

(c) Use the column orthogonality relations to calculate the product $\bar{Z}^T Z$, where $\bar{Z}^T$ is the transpose of the complex conjugate of $Z$.

(d) Calculate $|\det Z|$. 
12 The character table obtained in Question 9 is in fact the character table of the group $G = \text{PSL}_2(7)$ of $2 \times 2$ matrices with determinant 1 over the field $\mathbb{F}_7$ (of seven elements) modulo the two scalar matrices.

Deduce directly from the character table which you have obtained that $G$ is simple. [Comment: it is known that there are precisely five non-abelian simple groups of order less than 1000. The smallest of these is $A_5 \cong \text{PSL}_2(5)$, while $G$ is the second smallest. It is also known that for $p \geq 5$, $\text{PSL}_2(p)$ is simple.]

Identify the columns corresponding to the elements $x$ and $y$ where $x$ is an element of order 7 (eg the unitriangular matrix with 1 above the diagonal) and $y$ is an element of order 3 (eg the diagonal matrix with entries 4 and 2).

The group $G$ acts as a permutation group of degree 8 on the set of Sylow 7-subgroups (or the set of 1-dimensional subspaces of the vector space $(\mathbb{F}_7)^2$). Obtain the permutation character of this action and decompose it into irreducible characters.

Show that the group $G$ is generated by an element of order 2 and an element of order 3 whose product has order 7. [Hint: for the last part use the formula that the number of pairs of elements conjugate to $x$ and $y$ respectively, whose product is conjugate to $t$, equals $c \sum \chi(x)\chi(y)\chi(t^{-1})/\chi(1)$, where the sum runs over all the irreducible characters of $G$, and $c = |G|^2(|C_G(x)||C_G(y)||C_G(t)|^{-1}).$]
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 \( \text{SL}_2(\mathbb{F}_5) \) 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 \( \rho \) for \( G \) there is an irreducible representation \( \rho' \) for \( H \) with \( \rho \) a component of the induced representation \( \text{Ind}^G_H \rho' \).

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 \( C_m \). [Hint: consider the cases \( m \) odd and \( m \) even separately, as for \( m \) even there are two conjugacy classes of reflections, whereas for \( m \) odd there is only one.]

5 Prove the transitivity of induction: if \( H < K < G \) then

\[
\text{Ind}_K^G \text{Ind}_H^K \rho \cong \text{Ind}_H^G \rho
\]

for any representation \( \rho \) of \( H \).

6 (a) Let \( V = U \oplus W \) be a direct sum of \( CG \)-modules. Prove that both the symmetric square and the exterior square of \( V \) have submodules isomorphic to \( U \otimes W \).

(b) Calculate \( \chi_{A^2} \rho \) and \( \chi_{S^2} \rho \), where \( \rho \) 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?

7 Let \( \rho : G \to \text{GL}(V) \) 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 \( \chi_{A^n V}(g) \) from the coefficients of \( f(x) \).

(d)* Find a relation between \( \chi_{S^n V}(g) \) and the polynomial \( f(x) \). [Hint: first do the case when \( \dim V = 1 \).]
Let $G$ be the symmetric group $S_n$ acting naturally on the set $X = \{1, \ldots, n\}$. For any integer $r \leq \frac{n}{2}$, write $X_r$ for the set of all $r$-element subsets of $X$, and let $\pi_r$ be the permutation character of the action of $G$ on $X_r$. Observe $\pi_r(1) = |X_r| = \binom{n}{r}$. If $0 \leq \ell \leq k \leq n/2$, 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 $\chi^{(n)}$, $\chi^{(n-1,1)}$, $\chi^{(n-2,2)}$, $\ldots$, $\chi^{(n-m,m)}$ such that for all $r \leq m$, $$\pi_r = \chi^{(n)} + \chi^{(n-1,1)} + \chi^{(n-2,2)} + \cdots + \chi^{(n-r,r)}.$$ In particular the class functions $\pi_r - \pi_{r-1}$ are irreducible characters of $S_n$ for $1 \leq r \leq n/2$ and equal to $\chi^{(n-r,r)}$.

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

Define the Frobenius-Schur indicator $\iota_\chi$ of $\chi$ 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.]

If $\theta$ 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 $\theta$ 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 $a_1, \ldots, a_r$ of $\theta$ is nonsingular to obtain a contradiction.]

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 8.

Show by induction on $n$ that if the symmetric group $S_n$ with $n \geq 5$ has a complex irreducible representation $\rho$ of dimension $d \leq n$ then one of the following holds:

(i) $d = 1$, and $\rho$ is either the trivial representation 1 or the sign representation $\sigma$;
(ii) $d = n - 1$ and either $1 \oplus \rho$ or $1 \oplus \sigma \rho$ is the natural permutation representation;
(iii) $n = 5$ and $d = 5(= n)$ or $n = 6$ and $d = 5(= n - 1)$.

[Hint: Restrict $\rho$ to $S_{n-2} \times S_2$; it becomes reducible, unless it is linear; now use induction - what do linear representations of $S_{n-2} \times S_2$ get induced to?]
Unless otherwise stated, all vector spaces are finite-dimensional over $\mathbb{C}$. In the first nine questions we let $G = \text{SU}(2)$.

1. (a) Let $V_n$ be the vector space of complex homogeneous polynomials of degree $n$ in the variables $x$ and $y$. Describe a representation $\rho_n$ of $G$ on $V_n$ and show that it is irreducible. Describe the character $\chi_n$ of $\rho_n$.

(b) Decompose $V_4 \otimes V_3$ into irreducible $G$-spaces (that is, find a direct sum of irreducible representations which is isomorphic to $V_4 \otimes V_3$. In this and the following questions, you are not being asked to find such an isomorphism explicitly.)

(c) Decompose also $V_3 \otimes^2, \Lambda^2 V_3$ and $S^2 V_3$.

(d) Show that $V_n$ is isomorphic to its dual $V_n^*$.

2. Decompose $V_1^\otimes n$ into irreducibles.

3. Determine the character of $S^n V_1$ for $n \geq 1$.
Decompose $S^2 V_n$ and $\Lambda^2 V_n$ for $n \geq 1$.
Decompose $S^3 V_2$ into irreducibles.

4. Let $G$ act on the space $M_3(\mathbb{C})$ of $3 \times 3$ complex matrices, by
$$A : X \mapsto A_1 X A_1^{-1},$$
where $A_1$ is the $3 \times 3$ block diagonal matrix with block diagonal entries $A, 1$. Show that this gives a representation of $G$ and decompose it into irreducibles.

5. Let $\chi_n$ be the character of the irreducible representation $\rho_n$ of $G$ on $V_n$.
Show that
$$\frac{1}{2\pi} \int_0^{2\pi} K(z) \chi_n(z) \overline{x_m} d\theta = \delta_{nm},$$
where $z = e^{i\theta}$ and $K(z) = \frac{1}{2} (z - \frac{1}{z})(z^{-1} - \frac{1}{z})$.
[Note that all you need to know about integrating on the circle is orthogonality of characters: $\frac{1}{2\pi} \int_0^{2\pi} z^n d\theta = \delta_{n,0}$. This is really a question about Laurent polynomials.]

6. (a) Let $G$ be a compact group. Show that there is a continuous group homomorphism $\rho : G \to \text{O}(n)$ if and only if $G$ has an $n$-dimensional representation over $\mathbb{R}$. Here $\text{O}(n)$ denotes the subgroup of $\text{GL}_n(\mathbb{R})$ preserving the standard (positive definite) symmetric bilinear form.

(b) Explicitly construct such a representation $\rho : \text{SU}(2) \to \text{SO}(3)$ by showing that $\text{SU}(2)$ acts on the vector space of matrices of the form
$$\left\{ A = \begin{pmatrix} a & b \\ c & -a \end{pmatrix} \in M_2(\mathbb{C}) : A + \overline{A} = 0 \right\}$$
by conjugation. Show that this subspace is isomorphic to $\mathbb{R}^3$, that $(A, B) \mapsto -\text{tr}(AB)$ is a positive definite non-degenerate invariant bilinear form, and that $\rho$ is surjective with kernel $\{ \pm I \}$. 

7 Check that the usual formula for integrating functions defined on $S^3 \subseteq \mathbb{R}^4$ defines an $G$-invariant inner product on $G = \text{SU}(2) = \left\{ \begin{pmatrix} a & b \\ -\bar{b} & \bar{a} \end{pmatrix} : a\bar{a} + b\bar{b} = 1 \right\}$, and normalize it so that the integral over the group is one.

8 Suppose we are given that $H$ is a subgroup of order 24 in $G$. We are told that $H$ contains $\{\pm I\}$ as a normal subgroup, and that the quotient group $H/\{\pm I\}$ is isomorphic to $A_4$. Find the character table of $H$. [You may assume that $H$ has a conjugacy class containing six elements of order 4, two conjugacy classes each containing four elements of order 3, and two conjugacy classes each containing four elements of order 6.]

9 Compute the character of the representation $S^nV_2$ of $G$ for any $n \geq 0$. Calculate $\dim_{\mathbb{C}}(S^nV_2)^G$ (by which we mean the subspace of $S^nV_2$ where $G$ acts trivially).

Deduce that the ring of complex polynomials in three variables $x, y, z$ which are invariant under the action of $\text{SO}(3)$ is a polynomial ring. Find a generator for this polynomial ring.

10 The Heisenberg group of order $p^3$ is the (non-abelian) group $G = \left\{ \begin{pmatrix} 1 & a & x \\ 0 & 1 & b \\ 0 & 0 & 1 \end{pmatrix} : a, b, x \in \mathbb{F}_p \right\}$ of $3 \times 3$ upper unitriangular matrices over the finite field $\mathbb{F}_p$ of $p$ elements ($p$ prime).

Show that $G$ has $p$ conjugacy classes of size 1, and $p^2 - 1$ conjugacy classes of size $p$.

Find $p^2$ characters of degree 1.

Let $H$ be the subgroup of $G$ comprising matrices with $a = 0$. Let $\psi : \mathbb{F}_p \to \mathbb{C}^\times$ be a non-trivial 1-dimensional representation of the cyclic group $\mathbb{F}_p = \mathbb{Z}/p$, and define a 1-dimensional representation $\rho$ of $H$ by $\rho \left( \begin{pmatrix} 1 & 0 & x \\ 0 & 1 & b \\ 0 & 0 & 1 \end{pmatrix} \right) = \psi(x)$.

Check that $V_\psi = \text{Ind}^G_H\rho$ is irreducible.

Now list all the irreducible representations of $G$, explaining why your list is complete.

11 Recall Sheet 3, q.8 where we used inner products to construct some irreducible characters $\chi^{(n-r,r)}$ for $S_n$. Let $n \in \mathbb{N}$, and let $\Omega$ be the set of all ordered pairs $(i, j)$ with $i, j \in \{1, 2, \ldots, n\}$ and $i \neq j$. Let $G = S_n$ act on $\Omega$ in the obvious manner (namely, $\sigma(i, j) = (\sigma i, \sigma j)$ for $\sigma \in S_n$).

Let’s write $\pi^{(n-2,1,1)}$ for the permutation character of $S_n$ in this action.

Prove that $\pi^{(n-2,1,1)} = 1 + 2\chi^{(n-1,1)} + \chi^{(n-2,2)} + \psi$, where $\psi$ is an irreducible character. Writing $\psi = \chi^{(n-2,1,1)}$, calculate the degree of $\chi^{(n-2,1,1)}$. Find its value on any transposition and on any 3-cycle. Returning to the character table of $S_6$ calculated on Sheet 3 q.11, identify the character $\chi^{(4,1,1)}$.

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