

UNIVERSITY OF MISSOURI

MASTER'S PROJECT

A Survey on Character Tables for Representations of Finite Groups

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Chapter 1

Basic Notions of Representation Theory

1.1 Group Actions

Definition 1.1. A *(left) group action* of a group G on a set X is a map $\rho: G \times X \rightarrow X$ (written as $g \cdot a$, for all $g \in G$ and $a \in A$) that satisfies the following two axioms:

$$1 \cdot x = x \quad \forall x \in X \quad (1.1.1)$$

$$(gh) \cdot x = g \cdot (h \cdot x) \quad \forall g, h \in G, x \in X \quad (1.1.2)$$

Note. We could likewise define the concept of a *right* group action, where the set elements would be multiplied by group elements on the right instead of on the left. Throughout we shall use the term *group action* to mean a *left* group action.

Proposition 1.2. Let G act on the set X . For any fixed $g \in G$, the map σ_g from X into X defined by $\sigma_g(x) = g \cdot x$ is a permutation of the set X . That is, $\sigma_g \in S_X$.

Proof. We show that σ_g is a permutation of X by finding a two-sided inverse map, namely $\sigma_{g^{-1}}$. Observe that for any $x \in X$, we have

$$\begin{aligned} (\sigma_{g^{-1}} \circ \sigma_g)(x) &= \sigma_{g^{-1}}(\sigma_g(x)) \\ &= g^{-1} \cdot (g \cdot x) && \text{(by definition of } \sigma_g \text{ and } \sigma_{g^{-1}}) \\ &= (g^{-1}g) \cdot x && \text{(by axiom 1.1.1 of an action)} \\ &= 1 \cdot x \\ &= x && \text{(by axiom 1.1.2 of an action).} \end{aligned}$$

Thus $\sigma_{g^{-1}} \circ \sigma_g$ is the identity map on X . We can reverse the roles of g and g^{-1} to see that $\sigma_g \circ \sigma_{g^{-1}}$ is also the identity map on X . Having a two-sided inverse, we conclude that σ_g is a permutation of X . \square

Proposition 1.3. Let G act on the set X . The map from G into the symmetric group S_X defined by $g \mapsto \sigma_g(x) = g \cdot x$ is a group homomorphism.

Proof. Define the map $\rho: G \rightarrow S_X$ by $\rho(g) = \sigma_g$. We have seen from Proposition 1.2 that σ_g is indeed an element of S_X . It remains to show that $\rho(g_1g_2) = \rho(g_1) \circ \rho(g_2)$ for any $g_1, g_2 \in G$. Observe that

$$\begin{aligned}
\rho(g_1 g_2)(x) &= \sigma_{g_1 g_2}(x) && \text{(by definition of } \rho) \\
&= (g_1 g_2) \cdot x && \text{(by definition of } \sigma_{g_1 g_2}) \\
&= g_1 \cdot (g_2 \cdot x) && \text{(by axiom 1.1.1 of an action)} \\
&= \sigma_{g_1}(\sigma_{g_2}(x)) && \text{(by definition of } \sigma_{g_1} \text{ and } \sigma_{g_2}) \\
&= \rho(g_1)(\rho(g_2)(x)) && \text{(by definition of } \rho) \\
&= (\rho(g_1) \circ \rho(g_2))(x) && \text{(by definition of function composition).}
\end{aligned}$$

Since the values of $\rho(g_1 g_2)$ and $\rho(g_1) \circ \rho(g_2)$ agree on every element $x \in X$, these two permutations are equal. We conclude that ρ is a homomorphism, since g_1 and g_2 were arbitrary elements of G . \square

Proposition 1.4. Any homomorphism ψ from the group G into the symmetric group S_X on a set X gives rise to an action of G on X , defined by taking $g \cdot x = \psi(g)(x)$.

Proof. Suppose that we have a homomorphism ψ from G into S_X . We can define a map from $G \times X$ to X by $g \cdot x = \psi(g)(x)$. We verify that this map satisfies the definition of a group action of G on X :

$$\text{(axiom 1.1.1)} \quad 1 \cdot x = \psi(1)(x) = \text{id}_X(x) = x$$

$$\text{(axiom 1.1.2)} \quad (gh) \cdot x = \psi(gh)(x) = (\psi(g)\psi(h))(x) = \psi(g)(\psi(h)(x)) = g \cdot (h \cdot x) \quad \square$$

Corollary 1.5. The actions of G on the set X are in bijective correspondence with the homomorphisms from G into the symmetric group S_X .

Proof. By Proposition 1.3, any action of G on X yields a homomorphism from G into S_X . Conversely, any homomorphism from G into S_X establishes an action of G on X by Proposition 1.4. \square

1.2 The Definition of a Representation

Definition 1.6. Let G be a group. A **representation** of G is a homomorphism $\rho: G \rightarrow GL_n(\mathbb{C})$ for some positive integer n .

Definition 1.7. Two representations $\rho_1: G \rightarrow GL_n(\mathbb{C})$ and $\rho_2: G \rightarrow GL_n(\mathbb{C})$ of G are **equivalent** if there exists $P \in GL_n(\mathbb{C})$ such that $\rho_2 = P^{-1} \rho_1 P$.

Equivalent representations are fundamentally "the same" in some sense, but to make this precise we need to shift our thinking to linear maps instead of matrices.

Definition 1.8. Let G be a group, let F be a field, and let V be a vector space over F . A **linear representation** of G is any group homomorphism $\rho: G \rightarrow GL(V)$. If we fix a basis for V , we get a representation in the previous sense.

Definition 1.9 (Alternative definition). Let G be a group, let F be a field, and let V be a vector space over F . A **linear representation** of G is an action of G on V which preserves the linear structure of V , i.e. an action of G on V such that

$$g \cdot (v_1 + v_2) = g \cdot v_1 + g \cdot v_2 \quad \forall g \in G, v_1, v_2 \in V \quad (1.9.1)$$

$$g \cdot (kv) = k(g \cdot v) \quad \forall g \in G, v \in V, k \in F \quad (1.9.2)$$

Note. Unless otherwise specified, we use *representation* to mean *finite-dimensional complex representation*.

Proposition 1.10. *The definitions of a linear representation given in 1.8 and 1.9 above are equivalent.*

Proof. (\rightarrow) Suppose that we have a homomorphism $\rho: G \rightarrow GL(V)$. Note that $GL(V)$ is a subgroup of the symmetric group S_V on V , so we can apply Proposition 1.4 to obtain an action of G on V by $g \cdot v = \rho(g)(v)$. We check that this action preserves the linear structure of V .

1.9.1 For any $g \in G, v_1, v_2 \in V$ we have $g \cdot (v_1 + v_2) = \rho(g)(v_1 + v_2) = \rho(g)(v_1) + \rho(g)(v_2) = g \cdot v_1 + g \cdot v_2$.

1.9.2 For any $g \in G, v \in V, k \in F$ we have $g \cdot (kv) = \rho(g)(kv) = k(\rho(g)(v)) = k(g \cdot v)$.

(\leftarrow) Suppose that we have an action of G on V which preserves the linear structure of V in the sense of Definition 1.9. We can apply Proposition 1.3 to obtain a homomorphism $\rho: G \rightarrow S_V$ given by $\rho(g) = \sigma_g$ where $\sigma_g(v) = g \cdot v$. It remains to show that the image $\rho(G)$ of G under ρ is actually contained in $GL(V)$, i.e. that for each $g \in G$ the map σ_g is linear. Fix an element $g \in G$. For any $k \in F$ and $v \in V$, we have

$$\begin{aligned} \sigma_g(kv) &= g \cdot (kv) && \text{(by definition of } \sigma_g) \\ &= k(g \cdot v) && \text{(by property 1.9.1)} \\ &= k(\sigma_g(v)) && \text{(by definition of } \sigma_g). \end{aligned}$$

Also, for any $v_1, v_2 \in V$ we have

$$\begin{aligned} \sigma_g(v_1 + v_2) &= g \cdot (v_1 + v_2) && \text{(by definition of } \sigma_g) \\ &= g \cdot v_1 + g \cdot v_2 && \text{(by property 1.9.2)} \\ &= \sigma_g(v_1) + \sigma_g(v_2) && \text{(by definition of } \sigma_g). \end{aligned}$$

Thus σ_g is linear, and $\rho(G) \subset GL(V)$ proves that we have a homomorphism $\rho: G \rightarrow GL(V)$. □

Definition 1.11. Let G be a group, let F be a field, let V be a vector space over F , and let $\rho: G \rightarrow GL(V)$ be a representation of G . The **dimension** of the representation is the dimension of V over F .

Example 1.12. 1. Let V be a 1-dimensional vector space over the field F . The map $\rho: G \rightarrow GL(V)$ defined by $\rho(g) = 1$ for all $g \in G$ is a representation called the *trivial representation* of G . The trivial representation has dimension 1.

2. If G is a finite group that acts on a finite set X , and F is any field, then there is an associated *permutation representation* on the vector space V over F with basis $\{e_x: x \in X\}$. We let G act on the basis elements by the permutation $g \cdot e_x = e_{gx}$ for all $x \in X$ and $g \in G$. This representation has dimension $|X|$.
3. A fundamental special case of a permutation representation that we shall return to later on is that when a finite group acts on itself by left multiplication. In this case, the elements of G form a basis for V , and each $g \in G$ permutes the basis

elements by $g \cdot g_i = gg_i$. This representation is called the *regular representation* of G and has dimension $|G|$. We shall see later that this representation encodes information about all other representations of G .

4. For any symmetric group S_n , the *alternating representation* on $V = \mathbb{C}$ is given by the map $\rho: S_n \rightarrow GL(\mathbb{C}) = \mathbb{C}^\times$ defined by $\rho(\sigma) = \text{sgn}(\sigma)$. More generally, for any group G with a subgroup H of index 2, we can define an *alternating representation* $\rho: G \rightarrow GL(\mathbb{C})$ by letting $\rho(g) = 1$ if $g \in H$ and $\rho(g) = -1$ if $g \notin H$. (We recover our original example by taking $G = S_n$ and $H = A_n$.)

Definition 1.13. A **homomorphism** between two representations $\rho_1: G \rightarrow GL(V)$ and $\rho_2: G \rightarrow GL(W)$ is a linear map $\psi: V \rightarrow W$ that intertwines with (respects) the G -action, i.e. a map ψ such that

$$\psi(\rho_1(g)(v)) = \rho_2(g)(\psi(v)) \quad \forall v \in V, g \in G$$

An **isomorphism** of representations is a homomorphism of representations that is also an invertible map.

Note. If we have representations (ρ_1, V) and (ρ_2, W) and an isomorphism of vector spaces $\psi: V \rightarrow W$ then we can rewrite the compatibility requirement above as $\rho_2(g) = \psi \circ \rho_1(g) \circ \psi^{-1}$ for all $g \in G$.

Given any representation (ρ, V) of a group G on a vector space V over a field F of dimension n , we can fix a basis for V to obtain an isomorphism of vector spaces $\psi: V \rightarrow F^n$. This yields a representation ϕ of G on F^n by defining $\phi(g) = \psi \circ \rho(g) \circ \psi^{-1}$ for all $g \in G$. Clearly, this representation is isomorphic to our original representation (ρ, V) . In particular, this means we can always choose to view n -dimensional complex representations as representations on \mathbb{C}^n where each $\phi(g)$ is given by an $n \times n$ matrix with entries in \mathbb{C} .

Suppose that we have two representations $\rho_1: G \rightarrow GL_n(F)$ and $\rho_2: G \rightarrow GL_m(F)$ given by $\rho_1(g) = X_g$ and $\rho_2(g) = Y_g$. A homomorphism between these representations is then an $m \times n$ matrix A such that $AX_g = Y_gA$ for all $g \in G$. An isomorphism is given precisely when such A is square and invertible. Thus, two representations $\rho_1: G \rightarrow GL_n(F)$ and $\rho_2: G \rightarrow GL_n(F)$ are isomorphic if and only if there exists $A \in GL_n(F)$ such that $\rho_1(g) = A\rho_2(g)A^{-1}$ for all $g \in G$. This establishes the following proposition:

Proposition 1.14. *The isomorphism classes of n -dimensional representations of G on \mathbb{C} are in bijection with the quotient $\text{Hom}(G; GL_n(\mathbb{C}))/GL_n(\mathbb{C})$ of group homomorphisms $G \rightarrow GL_n(\mathbb{C})$ modulo the conjugation action of $GL_n(\mathbb{C})$.*

1.3 Representations of Cyclic Groups

Example 1.15 (Representations of \mathbb{Z}). We want to classify all representations of the group \mathbb{Z} under addition. Consider an n -dimensional representation $\rho: \mathbb{Z} \rightarrow GL_n(\mathbb{C})$. For ρ to be a group homomorphism requires that $\rho(0) = \text{Id}$. Observe that for any $0 \neq n \in \mathbb{Z}$, we have $\rho(n) = \rho(1 + \dots + 1) = \rho(1)^n$. Thus ρ is completely determined by the matrix $\rho(1) \in GL_n(\mathbb{C})$, and any such matrix determines a representation of \mathbb{Z} . It follows that the n -dimensional isomorphism classes of representations of \mathbb{Z} are in bijection with the conjugacy classes in $GL_n(\mathbb{C})$. These conjugacy classes can be parameterized by the *Jordan canonical form*.

Example 1.16 (Representations of the cyclic group of order n). We shall classify all representations of the cyclic group $G = \{g, g^2, \dots, g^{n-1}, g^n = 1\}$ of order n . Consider a representation $\rho: G \rightarrow GL(V)$. As in the previous example, we know that $\rho(1) = \text{Id}$ and $\rho(g^k) = \rho(g)^k$. Thus our representation ρ is determined completely by the linear transformation $\rho(g)$. It will be helpful to fix a basis of V so that we may view $\rho(g)$ as a matrix. Recall from linear algebra that there exists a basis in which $\rho(g)$ takes the *Jordan canonical form*

$$\rho(g) = \begin{bmatrix} J_1 & 0 & \dots & 0 \\ 0 & J_2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & J_m \end{bmatrix}$$

where each *Jordan block* J_k is of the form

$$J_k = \begin{bmatrix} \lambda & 1 & 0 & \dots & 0 & 0 \\ 0 & \lambda & 1 & \ddots & 0 & 0 \\ 0 & 0 & \lambda & \ddots & 0 & 0 \\ 0 & 0 & 0 & \ddots & 1 & 0 \\ \vdots & \ddots & \ddots & \ddots & \ddots & 1 \\ 0 & 0 & 0 & \dots & 0 & \lambda \end{bmatrix}.$$

Now $I = \rho(g)^n$ is a block-diagonal matrix with diagonal blocks J_k^n , so we must have that each block $J_k^n = \text{Id}$. Observe that we can write each block J_k as $J_k = \lambda \text{Id} + N$ where N is the Jordan block with $\lambda = 0$. Thus we have

$$\text{Id} = J_k^n = (\lambda \text{Id} + N)^n = \lambda^n \text{Id} + \binom{n}{1} \lambda^{n-1} N + \binom{n}{2} \lambda^{n-2} N^2 + \dots + \binom{n}{n-1} \lambda N^{n-1} + N^n$$

. The following lemma will show that in fact $N = 0$.

Lemma 1.17. *Let N be the Jordan block with $\lambda = 0$ of size $n \times n$. For any integer p with $1 \leq p \leq n-1$, then N^p is the matrix with ones in the positions (i, j) where $j = i + p$ and zeroes everywhere else. (The ones lie along a line parallel to the diagonal, p steps above it.)*

Proof. (By induction.)

Base case: This is simply the definition of N .

Inductive step: Suppose that the lemma holds for N^p . We compute the (i, j) entry of N^{p+1} :

$$(N^{p+1})_{i,j} = \sum_{k=1}^n (N^p)_{i,k} N_{k,j} = (N^p)_{i,i+p} N_{i+p,j} = N_{i+p,j} = \begin{cases} 1 & \text{if } j = i + (p+1) \\ 0 & \text{otherwise} \end{cases}$$

□

Now, if $N \neq 0$ then each term $\binom{n}{k} \lambda^{n-k} N^k$ for $k > 0$ would yield some non-zero non-diagonal entries (in the positions (i, j) where $j = i + k$) and hence our sum could not equal the identity matrix. We must conclude that $N = 0$, $J_k = \lambda \text{Id}$ is a 1×1 block, and $J_k^n = \lambda^n \text{Id}$. Thus $\rho(g)$ is a diagonal matrix with n th roots of unity as diagonal entries.

To summarize, every m -dimensional representation ρ of the cyclic group $G = \langle g \rangle$ of order n can be seen to act (with the right choice of basis) as $m \times m$ diagonal matrices all with n th roots of unity along the diagonal. In particular, these representations are determined completely by the value of $\rho(g)$ and are classified up to isomorphism by unordered m -tuples of n th roots of unity.

1.4 Constructions from Linear Algebra

Definition 1.18. A **subrepresentation** of V is a G -invariant subspace $W \subseteq V$; that is, a subspace $W \subseteq V$ with the property that $\rho(g)(w) \in W$ for all $g \in G$ and $w \in W$. Note that W itself is a representation of G under the action $\rho(g)|_W$.

From elementary linear algebra, we know that given a subspace $W \subseteq V$, we can form the **quotient space** V/W consisting of cosets $v + W$ in V . If W is a subrepresentation of V , we would like to define an action of G on V/W by the natural choice of $g(v + W) = \rho(g)(v) + W$. It remains to verify that this action is well defined. If we choose another $v' \in v + W$, then $v - v' \in W$, so that $\rho(g)(v - v') \in W$ since W is G -invariant. Thus, the cosets $\rho(g)(v) + W$ and $\rho(g)(v') + W$ agree and this action is indeed well defined. This justifies the following definition:

Definition 1.19. Let W be a G -subrepresentation of V . Then V/W forms a representation of G called the **quotient representation** of V under W with the action $g(v + W) = \rho(g)(v) + W$.

Recall also from linear algebra that given two vector spaces V_1 and V_2 , we can form the **direct sum** $V_1 \oplus V_2$ consisting of ordered pairs (v_1, v_2) where $v_1 \in V_1, v_2 \in V_2$.

Definition 1.20. Let V_1 and V_2 be representations of G . Then $V_1 \oplus V_2$ forms a representation of G called the **direct sum representation** of V_1 and V_2 with the action $g(v_1, v_2) = (g \cdot v_1, g \cdot v_2)$.

1.5 Complete Reducibility and Unitarity

Definition 1.21. A representation is said to be **irreducible** if it contains no proper invariant subspaces. It is called **completely reducible** if it decomposes into a direct sum of irreducible subrepresentations.

Example 1.22. 1. Any irreducible representation is completely reducible.

2. Any 1-dimensional representations has no proper subspaces, and is thus irreducible.

Theorem 1.23. If A_1, A_2, \dots, A_r are linear operators on V and each A_i is diagonalizable, they are simultaneously diagonalizable if and only if they commute.

Proof. See Conrad [2, Theorem 5.1]. □

Theorem 1.24. Every complex representation of a finite abelian group is completely reducible into irreducible representations of dimension 1.

Proof. Take an arbitrary element $g \in G$. Since G is finite, we can find an integer n such that $g^n = 1$ and $\rho(g)^n = Id$. Hence the minimal polynomial of $\rho(g)$ divides $x^n - 1$. Recall that $x^n - 1$ has n distinct roots over \mathbb{C} , which are generated by taking powers of $\xi = e^{\frac{2\pi i}{n}}$. This means that the minimal polynomial $\rho(g)$ factors into linear factors only over \mathbb{C} so that $\rho(g)$ is diagonalizable. We conclude that each $\rho(g)$ is (separately) diagonalizable since $g \in G$ was arbitrary.

Now, given any two elements $g_1, g_2 \in G$ we have

$$\begin{aligned} \rho(g_1)\rho(g_2) &= \rho(g_1g_2) && \text{(since } \rho \text{ is a homomorphism)} \\ &= \rho(g_2g_1) && \text{(since } G \text{ is abelian)} \\ &= \rho(g_2)\rho(g_1) && \text{(since } \rho \text{ is a homomorphism).} \end{aligned}$$

Thus the matrices $\{\rho(g)\}$ commute, so we may apply theorem 1.23 to conclude that $\{\rho(g)\}$ are simultaneously diagonalizable, say with basis $\{e_1, \dots, e_k\}$. Then we have $V = \mathbb{C}e_1 \oplus \mathbb{C}e_2 \oplus \dots \oplus \mathbb{C}e_n$, with each subspace $\mathbb{C}e_i$ invariant under the action of G . \square

We recall the following definition from linear algebra:

Definition 1.25. Let V be a complex vector space. A **Hermitian inner product** on V is a map $\langle \cdot, \cdot \rangle: V \times V \rightarrow \mathbb{C}$ that satisfies the following properties for all $u, v, w \in V$ and $c \in \mathbb{C}$:

1. $\langle u + v, w \rangle = \langle u, w \rangle + \langle v, w \rangle$.
2. $\langle cu, v \rangle = c\langle u, v \rangle$.
3. $\langle u, v \rangle = \overline{\langle v, u \rangle}$.
4. $\langle v, v \rangle \geq 0$ with equality if and only if $v = 0$.

Definition 1.26. A representation ρ of G on a complex vector space V is **unitary** if V has been equipped with a hermetian inner product $\langle \cdot, \cdot \rangle$ which is preserved by the action of G , that is,

$$\langle v, w \rangle = \langle \rho(g)(v), \rho(g)(w) \rangle \quad \forall v, w \in V, g \in G.$$

A representation is said to be **unitarisable** if it can be equipped with such a product (even without one being specified).

Theorem 1.27. [Weyl's unitary trick] *Finite-dimensional representations of finite groups are unitarisable.*

Proof. Take any Hermitian inner product on V , say $\langle \cdot, \cdot \rangle'$. We define a new inner product on V by averaging over G :

$$\langle v, w \rangle := \frac{1}{|G|} \sum_{g \in G} \langle \rho(g)v, \rho(g)w \rangle'.$$

This new inner product satisfies properties 1, 2, and 3 of Definition 1.25 by linearity. It remains to check positivity (4). Clearly $\langle v, v \rangle = 0$ when $v = 0$, since each term of the sum will equal zero. In the case where $v \neq 0$, observe that

$$\langle v, v \rangle = \frac{1}{|G|} \sum_{g \in G} \langle \rho(g)v, \rho(g)v \rangle' \geq 0$$

since each term of the sum is non-negative by the positivity of $\langle \cdot, \cdot \rangle'$. The only problem would occur if each term of this sum is equal to zero. But $\langle \rho(e)v, \rho(e)v \rangle' = \langle v, v \rangle' > 0$. Thus $\langle v, v \rangle > 0$.

Finally, we show that our new inner product is G -invariant. For any $h \in G$, we have

$$\begin{aligned} \langle \rho(h)v, \rho(h)w \rangle &= \frac{1}{|G|} \sum_{g \in G} \langle \rho(g)\rho(h)v, \rho(g)\rho(h)w \rangle' \\ &= \frac{1}{|G|} \sum_{g \in G} \langle \rho(gh)v, \rho(gh)w \rangle' && \text{(since } \rho \text{ is a homomorphism)} \\ &= \frac{1}{|G|} \sum_{k \in G} \langle \rho(k)v, \rho(k)w \rangle' && \text{(by a change of variables)} \\ &= \langle v, w \rangle. \end{aligned}$$

□

Lemma 1.28. *Let V be a unitary representation of G and let $W \subseteq V$ be a G -invariant subspace. Then the orthogonal complement W^\perp is also G -invariant.*

Proof. Choose arbitrary elements $v \in W^\perp$ and $g \in G$. We need to show that $gv \in W^\perp$. Now for any $w \in W$, we have $\langle v, w \rangle = 0$. Thus $\langle gv, gw \rangle = g\bar{g}\langle v, w \rangle = 0$ for any $w \in W$. Notice that $w' = gw \in W$ since W is G -invariant. This implies that $\langle gv, w' \rangle = 0$, i.e. $gv \in W^\perp$. □

Theorem 1.29. *A finite-dimensional unitary representation of a group is fully reducible into unitary irreducible subrepresentations.*

Proof. Let V be a finite dimensional unitary representation of G . We proceed by induction on the dimension of V . If $\dim(V) = 1$, then V is necessarily irreducible. Now, suppose the theorem holds for all W with $\dim(V) \leq n - 1$ and suppose $\dim(V) = n$. If V is irreducible, we are done. Otherwise, there exists a proper G -invariant subspace $W (\neq 0, V)$. We can write $V = W \oplus W^\perp$ by Lemma 1.28. Applying the inductive hypothesis to W and W^\perp , we obtain a decomposition into irreducibles

$$V = (W_1 \oplus \dots \oplus W_j) \oplus (W_{j+1} \oplus \dots \oplus W_k).$$

□

Corollary 1.30. *Every complex representation of a finite group is completely reducible.*

Proof. Any such representation is unitarisable by Theorem 1.27. We can apply Theorem 1.29 to obtain full reducibility. □

1.6 Vector Spaces of Linear Maps

Definition 1.31. Let V and W be vector spaces. Recall that the set $\mathbf{Hom}(V, W)$ of linear maps from V to W is itself a vector space. If f_1, f_2 are two linear maps from V to W , then we define their sum by

$$\begin{aligned} (f_1 + f_2): V &\rightarrow W \\ x &\mapsto f_1(x) + f_2(x) \end{aligned}$$

and we define scalar multiplication of $\lambda \in \mathbb{C}$ by

$$\begin{aligned} (\lambda f_1): V &\rightarrow W \\ x &\mapsto \lambda f_1(x). \end{aligned}$$

Now suppose we have representations $\rho_V: G \rightarrow GL(V)$ and $\rho_W: G \rightarrow GL(W)$ of G . Then there is a natural representation of G on the vector space $\text{Hom}(V, W)$ given by

$$\begin{aligned} \rho_{\text{Hom}(V, W)}(g): \text{Hom}(V, W) &\rightarrow \text{Hom}(V, W) \\ f &\mapsto \rho_W(g) \circ f \circ \rho_V(g^{-1}) \end{aligned}$$

for all $g \in G$. Note that $\rho_{\text{Hom}(V, W)}(g)(f)$ is certainly a linear map from V to W since the composition of linear maps is linear.

Proposition 1.32. $\rho_{\text{Hom}(V, W)}$ is a representation of G . That is, the map

$$\begin{aligned} \rho_{\text{Hom}(V, W)}: G &\rightarrow GL(\text{Hom}(V, W)) \\ g &\mapsto \rho_{\text{Hom}(V, W)}(g). \end{aligned}$$

is a homomorphism.

Proof. We must check two things:

1. The map $g \mapsto \rho_{\text{Hom}(V, W)}(g)$ is a homomorphism.
2. For every $g \in G$, $\rho_{\text{Hom}(V, W)}(g)$ is invertible.

First, we check that

$$\begin{aligned} \rho_{\text{Hom}(V, W)}(g) \circ \rho_{\text{Hom}(V, W)}(h): f &\mapsto \rho_{\text{Hom}(V, W)}(g)(\rho_W(h) \circ f \circ \rho_V(h^{-1})) \\ &= \rho_W(g) \circ \rho_W(h) \circ f \circ \rho_V(h^{-1}) \circ \rho_V(g^{-1}) \\ &= \rho_W(gh) \circ f \circ \rho_V(g^{-1}h^{-1}) \\ &= \rho_{\text{Hom}(V, W)}(gh)(f) \end{aligned}$$

so indeed $\rho_{\text{Hom}(V, W)}$ is a homomorphism. We can use this fact to see that $\rho_{\text{Hom}(V, W)}(g^{-1})$ is inverse to $\rho_{\text{Hom}(V, W)}(g)$ as

$$\begin{aligned} \rho_{\text{Hom}(V, W)}(g) \circ \rho_{\text{Hom}(V, W)}(g^{-1}) &= \rho_{\text{Hom}(V, W)}(e) \\ &= \text{Id}_{\text{Hom}(V, W)} \\ &= \rho_{\text{Hom}(V, W)}(g^{-1}) \circ \rho_{\text{Hom}(V, W)}(g). \end{aligned}$$

Thus $\rho_{\text{Hom}(V, W)}(g)$ is invertible for every $g \in G$, and $\rho_{\text{Hom}(V, W)}$ is a representation of G . \square

Definition 1.33. Let V and W be two representations of G . The set of G -linear maps from V to W forms a subspace of $\text{Hom}(V, W)$, which we denote by $\mathbf{Hom}_G(V, W)$. In other words, $\text{Hom}_G(V, W)$ is the vector space consisting of all *homomorphisms of representations* between V and W .

Definition 1.34. Let $\rho: G \rightarrow GL(V)$ be a representation. We define the **invariant subrepresentation** $V^G \subset V$ to be the set

$$\{v \in V \mid \rho(g)(v) = v, \quad \forall g \in G\}.$$

Note that V^G is a subspace of V , and is also clearly a subrepresentation. It is isomorphic to a trivial representation of some dimension.

Proposition 1.35. *Let $\rho_V: G \rightarrow GL(V)$ and $\rho_W: G \rightarrow GL(W)$ be representations of G . Then the subrepresentation*

$$\text{Hom}_G(V, W) \subset \text{Hom}(V, W)$$

is precisely the invariant subrepresentation $\text{Hom}(V, W)^G$ of $\text{Hom}(V, W)$.

Proof. Let $f \in \text{Hom}(V, W)$. Then f is an element of the invariant subrepresentation $\text{Hom}(V, W)^G$ iff we have

$$\begin{aligned} f &= \rho_{\text{Hom}(V, W)}(g)(f) \quad \forall g \in G \\ \iff f &= \rho_W(g) \circ f \circ \rho_V(g^{-1}) \quad \forall g \in G \\ \iff f \circ \rho_V(g) &= \rho_W(g) \circ f \quad \forall g \in G \end{aligned}$$

which is exactly the condition that f is G -linear, i.e. that $f \in \text{Hom}_G(V, W)$. \square

Lemma 1.36. *Let A and B be two representations of G . Then*

$$(A \oplus B)^G = A^G \oplus B^G.$$

Proof. Observe that

$$\begin{aligned} (a, b) \in (A \oplus B)^G &\iff \rho_{A \oplus B}(g)(a, b) = (a, b) && \forall g \in G \\ &\iff (\rho_A(g)(a), \rho_B(g)(b)) = (a, b) && \forall g \in G \\ &\iff (a, b) \in A^G \oplus B^G. \end{aligned}$$

\square

Lemma 1.37. *Let $\psi: A \rightarrow B$ be an isomorphism between representations of G . Then ψ induces an isomorphism between their invariant subrepresentations*

$$\psi|_{A^G}: A^G \rightarrow B^G.$$

Proof. Clearly the restriction of ψ to $A^G \subset A$ induces an isomorphism to some subrepresentation of B , but we must check that the image of this restriction actually equals B^G . We verify that

$$\begin{aligned} a \in A^G &\iff \rho_A(g)(a) = a && \forall g \in G \\ &\iff \psi(\rho_A(g)(a)) = \psi(a) && \forall g \in G \\ &\iff \rho_B(g)\psi(a) = \psi(a) && \forall g \in G \\ &\iff \psi(a) \in B^G. \end{aligned}$$

\square

1.7 Schur's Lemma

Theorem 1.38. *[Schur's Lemma over \mathbb{C} .] If V is an irreducible G -representation over \mathbb{C} , then every linear operator $\phi: V \rightarrow V$ commuting with G is a scalar.*

Proof. Let λ be an eigenvalue of ϕ . Observe that the eigenspace E_λ is G -invariant: If $v \in E_\lambda$, then $\phi(v) = \lambda v$. This implies that $\phi(gv) = g\phi(v) = g(\lambda v) = \lambda(gv)$, i.e. $gv \in E_\lambda$. Since g was arbitrary, E_λ is indeed G -invariant. Now $E_\lambda \neq 0$, so by irreducibility $E_\lambda = V$. Thus $\phi = \lambda \text{Id}$. \square

Corollary 1.39. *If V and W are irreducible, the space $\text{Hom}_G(V, W)$ is 1-dimensional if the representations are isomorphic, and in this case any non-zero map is an isomorphism. Otherwise, $\text{Hom}^G(V, W) = \{0\}$.*

Proof. We claim $\ker(\phi)$ and $\text{im}(\phi)$ are both G -invariant. Let $0 \neq \phi \in \text{Hom}_G(V, W)$. If $v \in \ker(\phi)$, then $\phi(v) = 0$ implies that $\phi(gv) = g\phi(v) = g0 = 0$, i.e. $gv \in \ker(\phi)$. Similarly, if $v \in \text{im}(\phi)$, then $v = \phi(w)$ implies that $\phi(gw) = g\phi(w) = gv$, i.e. $gv \in \text{im}(\phi)$.

Irreducibility yields $\ker(\phi) = 0$ or V and $\text{im}(\phi) = 0$ or W as the only possibilities. If $\phi \neq 0$, then $\ker(\phi) = 0$. This means that ϕ is injective, $\text{im}(\phi) = W$, and ϕ is an isomorphism.

Let ψ be another intertwining operator from V to W . Then $\phi^{-1} \circ \psi$ is also an intertwining operator from V to V . We can apply Schur's Lemma over \mathbb{C} to see that $\phi^{-1} \circ \psi = \lambda \text{Id}$, hence $\psi = \lambda \phi$. \square

More definitions are required before we can state a more general Schur's Lemma (not restricted to just \mathbb{C}).

Definition 1.40. An **algebra** over a field K is a ring with unit, containing a distinguished copy of K that commutes with every algebra element, and with $1 \in K$ being the algebra unit. A **division ring** is a ring where every non-zero element is invertible, and a **division algebra** is a division ring which is also a K -algebra.

Definition 1.41. Let V be a representation of G over K . The **endomorphism algebra** $\text{End}^G(V)$ is the space of linear self-maps $\phi: V \rightarrow V$ which commute with the group action, that is, $\rho(g) \circ \phi = \phi \circ \rho(g) \quad \forall g \in G$. The addition is the usual addition of linear maps (pointwise), and the multiplication is function composition. The distinguished copy of K is given by $K\text{Id}$.

Theorem 1.42. [Schur's Lemma] *If V is an irreducible finite-dimensional representation of G over K , then $\text{End}^G(V)$ is a finite-dimensional division algebra over K .*

1.8 Isotypical Decomposition

Lemma 1.43. *Let U, V, W be three vector spaces. Then we have natural isomorphisms*

1. $\text{Hom}(V, U \oplus W) = \text{Hom}(V, U) \oplus \text{Hom}(V, W)$
2. $\text{Hom}(U \oplus W, V) = \text{Hom}(U, V) \oplus \text{Hom}(W, V)$.

Additionally, if U, V, W carry representations of G , then (1) and (2) are isomorphisms of representations.

Proof. We have inclusion and projection maps

$$U \begin{array}{c} \xrightarrow{\iota_U} \\ \xleftarrow{\pi_U} \end{array} U \oplus W \begin{array}{c} \xrightarrow{\pi_W} \\ \xleftarrow{\iota_W} \end{array} W$$

given by

$$\begin{aligned}\iota_U &: x \mapsto (x, 0) \\ \pi_U &: (x, y) \mapsto x\end{aligned}$$

and similarly for ι_W and π_W . It is clear that

$$\text{Id}_{U \oplus W} = \iota_U \circ \pi_U + \iota_W \circ \pi_W.$$

We also note that the four spaces under consideration all have dimension $(\dim V)(\dim W + \dim U)$.

(1) We define a map

$$\begin{aligned}\psi &: \text{Hom}(V, U \oplus W) \rightarrow \text{Hom}(V, U) \oplus \text{Hom}(V, W) \\ f &\mapsto (\pi_U \circ f, \pi_W \circ f).\end{aligned}$$

We claim that this map has an inverse given by

$$\begin{aligned}\psi^{-1} &: \text{Hom}(V, U) \oplus \text{Hom}(V, W) \rightarrow \text{Hom}(V, U \oplus W) \\ (f_U, f_W) &\mapsto \iota_U \circ f_U + \iota_W \circ f_W.\end{aligned}$$

Check that

$$\begin{aligned}\psi^{-1} \circ \psi &: f \mapsto \iota_U \circ \pi_U \circ f + \iota_W \circ \pi_W \circ f \\ &= (\iota_U \circ \pi_U + \iota_W \circ \pi_W) \circ f \\ &= \text{Id}_{\text{Hom}(V, W)} \circ f = f.\end{aligned}$$

Since both vector spaces have the same dimension, $\psi \circ \psi^{-1}$ must be the identity map as well, and ψ is an isomorphism of vector spaces. Now suppose we have representations ρ_V, ρ_W, ρ_U of G on V, W and U . Then we claim ψ is G -linear. Recall that by definition,

$$\rho_{\text{Hom}(V, U \oplus W)}(g)(f) = \rho_{U \oplus W}(g) \circ f \circ \rho_V(g^{-1}).$$

Observe that for any $g \in G$ and $f \in \text{Hom}(V, U \oplus W)$,

$$\begin{aligned}\pi_U \circ (\rho_{\text{Hom}(V, U \oplus W)}(g)(f)) &= \pi_U \circ \rho_{U \oplus W}(g) \circ f \circ \rho_V(g^{-1}) \\ &= \rho_U(g) \circ \pi_U \circ f \circ \rho_V(g^{-1}) \quad (\text{since } \pi_U \text{ is } G\text{-linear}) \\ &= \rho_{\text{Hom}(U, V)}(g)(f)\end{aligned}$$

and similarly for W , so that

$$\begin{aligned}\psi(\rho_{\text{Hom}(V, U \oplus W)}(g)(f)) &= (\pi_U \circ \rho_{\text{Hom}(V, U \oplus W)}(g)(f), \pi_W \circ \rho_{\text{Hom}(V, U \oplus W)}(g)(f)) \\ &= (\rho_{\text{Hom}(V, U)}(g)(\pi_U \circ f), \rho_{\text{Hom}(V, W)}(g)(\pi_W \circ f)) \\ &= \rho_{\text{Hom}(V, U) \oplus \text{Hom}(V, W)}(g)(\pi_U \circ f, \pi_W \circ f).\end{aligned}$$

Thus ψ is G -linear, and we've proved (1).

(2) Define a map

$$\begin{aligned}\phi &: \text{Hom}(U \oplus W, V) \rightarrow \text{Hom}(U, V) \oplus \text{Hom}(W, V) \\ &= (f \circ \iota_U, f \circ \iota_W).\end{aligned}$$

We [finish me]. The book says proof is like (1) □

Corollary 1.44. *If U, V, W are representations of G , then there are natural isomorphisms*

$$1. \operatorname{Hom}_G(V, U \oplus W) = \operatorname{Hom}_G(V, U) \oplus \operatorname{Hom}_G(V, W)$$

$$2. \operatorname{Hom}_G(U \oplus W, V) = \operatorname{Hom}_G(U, V) \oplus \operatorname{Hom}_G(W, V)$$

Proof. (1). By Lemma (1.43), we have an isomorphism of representations

$$\psi: \operatorname{Hom}(V, U \oplus W) \rightarrow \operatorname{Hom}(V, U) \oplus \operatorname{Hom}(V, W).$$

We can apply Lemma (1.37) to obtain an isomorphism on the invariant subrepresentations

$$\operatorname{Hom}(V, U \oplus W)^G \cong (\operatorname{Hom}(V, U) \oplus \operatorname{Hom}(V, W))^G.$$

Then Lemma (1.36) implies that

$$\operatorname{Hom}(V, U \oplus W)^G \cong \operatorname{Hom}(V, U)^G \oplus \operatorname{Hom}(V, W)^G.$$

The statement now follows from Proposition (1.35). □

(2). The argument is similar to the one above. □

Proposition 1.45. *Let V and W be irreducible representations of G . Then*

$$\dim \operatorname{Hom}_G(V, W) = \begin{cases} 1 & \text{if } V \text{ and } W \text{ are isomorphic} \\ 0 & \text{if } V \text{ and } W \text{ are not isomorphic} \end{cases}$$

Proof. Suppose V and W are not isomorphic. Then Schur's Lemma states that the only G -linear map from V to W is the zero map, hence $\operatorname{Hom}_G(V, W) = \{0\}$.

On the other hand, suppose that $f: V \rightarrow W$ is an isomorphism. Then for any $h \in \operatorname{Hom}_G(V, W)$, we have $f^{-1} \circ h \in \operatorname{Hom}_G(V, V)$. By Schur's Lemma, $f^{-1} \circ h = \lambda \operatorname{Id}_V$ for some $\lambda \in \mathbb{C}$, i.e. $h = \lambda f$. Thus f spans $\operatorname{Hom}_G(V, W)$. □

Proposition 1.46. *Let $\rho: G \rightarrow GL(V)$ be a representation, and let*

$$V = U_1 \oplus \dots \oplus U_s$$

be a decomposition of V into irreducibles. Let W be any irreducible representation of G . Then the number of irreducible representations in the set $\{U_1, \dots, U_s\}$ which are isomorphic to W is equal to the dimension of $\operatorname{Hom}_G(V, W)$, and also equal to the dimension of $\operatorname{Hom}_G(W, V)$.

Proof. We know from Proposition (1.45) that the number of irreducible representations in the set $\{U_1, \dots, U_s\}$ which are isomorphic to W is equal to

$$\sum_{i=1}^s \dim \operatorname{Hom}_G(U_i, W).$$

By Corollary (1.44),

$$\operatorname{Hom}_G(V, W) = \bigoplus_{i=1}^s \operatorname{Hom}_G(U_i, W)$$

so that

$$\dim \operatorname{Hom}_G(V, W) = \sum_{i=1}^s \dim \operatorname{Hom}_G(U_i, W).$$

The same argument works if we consider $\text{Hom}_G(W, V)$ and $\text{Hom}_G(W, U_i)$ in place of $\text{Hom}_G(V, W)$ and $\text{Hom}_G(U_i, W)$. \square

Theorem 1.47. *Let $\rho: G \rightarrow GL(V)$ be a representation, and let*

$$V = U_1 \oplus \dots \oplus U_s$$

$$V = \tilde{U}_1 \oplus \dots \oplus \tilde{U}_r$$

be two decompositions of V into irreducible subrepresentations. Then $s = r$, and (after reordering if necessary) U_i and \tilde{U}_i are isomorphic for every $i \in \{1, \dots, s\}$.

Proof. Let W be any irreducible representation of G . By Proposition (1.46), the number of irreducible subrepresentations in the first decomposition that are isomorphic to W is equal to $\dim \text{Hom}_G(V, W)$. On the other hand, the number of irreducible subrepresentations in the second decomposition that are isomorphic to W is also equal to $\dim \text{Hom}_G(V, W)$. So for any irreducible representation W , the two decompositions contain the same number of factors isomorphic to W . \square

1.9 Tensor Product

Definition 1.48. Suppose V and W are two vector spaces over a field K . Then we define a new vector space called the **tensor product** of V and W , denoted by $V \otimes_K W$. This space is the quotient of the free vector space on $V \times W$ (with basis given by formal symbols $v \otimes w, v \in V, w \in W$), by the subspace D spanned by all elements of the form

$$\begin{aligned} (v_1 + v_2, w) - (v_1, w) - (v_2, w) \\ (v, w_1 + w_2) - (v, w_1) - (v, w_2) \\ (k \cdot v, w) - (v, k \cdot w) \end{aligned}$$

for $v, v_1, v_2 \in V, w, w_1, w_2 \in W$, and $k \in K$. When the ground field K is clear it can be omitted from the notation. The elements of $V \otimes W$ are called **tensors**, and the coset $v \otimes w$ of (v, w) in $V \otimes W$ is called a **simple tensor**. We have the relations

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

Definition 1.49. Let V and W be vector spaces over K . A map $\phi: V \times W \rightarrow K$ is called **K -balanced** if

$$\begin{aligned} \phi(v_1 + v_2, w) &= \phi(v_1, w) + \phi(v_2, w) \\ \phi(v, w_1 + w_2) &= \phi(v, w_1) + \phi(v, w_2) \\ \phi(v, kw) &= \phi(kv, w) \end{aligned}$$

for all $v \in V, w \in W, k \in K$.

Example 1.50. Mapping $V \times W$ to the free K -vector space on $V \times W$, and then passing to the quotient defines a map $\iota: V \times W \rightarrow V \otimes W$ with $\iota(v, w) = v \otimes w$. From the relations satisfied by the tensor product, we see that the map ι is K -balanced.

Theorem 1.51. [Universal property of the tensor product] Suppose V, W , and U are vector spaces over the field K . Let $\varphi: V \times W \rightarrow U$ be a K -balanced map, and let ι be the map above. Then there is a unique linear map $\varphi: V \otimes W \rightarrow U$ such that φ factors through ι , i.e., $\varphi = \varphi \circ \iota$.

Proof. The map φ extends by linearity to a linear transformation $\tilde{\varphi}$ from the free vector space on $V \times W$ to U such that $\tilde{\varphi}(v, w) = \varphi(v, w)$ for all $v \in V, w \in W$. Since φ is K -balanced, $\tilde{\varphi}$ maps each of the elements which span the subspace D from the definition of the tensor product to 0. For example,

$$\tilde{\varphi}((kv, w) - (v, kw)) = \varphi(kv, w) - \varphi(v, kw) = 0.$$

Thus the kernel of $\tilde{\varphi}$ contains D , and so $\tilde{\varphi}$ induces a linear map $\varphi: V \otimes W \rightarrow U$. Then

$$\varphi(v \otimes w) = \tilde{\varphi}(v, w) = \varphi(v, w)$$

i.e., $\varphi = \varphi \circ \iota$. Note that φ is completely determined by this equation since the elements $v \otimes w$ span $V \otimes W$. \square

Proposition 1.52. Let $\{e_i\}_{i \in I}$ and $\{f_j\}_{j \in J}$ be bases for V and W . Then $\{e_i \otimes f_j \mid i \in I, j \in J\}$ is a basis for $V \otimes W$.

Proof. An elementary tensor in $V \otimes W$ has the form $v \otimes w$. Write $v = \sum_i a_i e_i$ and $w = \sum_j b_j f_j$, where all but finitely many of a_i and b_j are 0. Then

$$m \otimes n = \sum_i a_i e_i \otimes \sum_j b_j f_j = \sum_{i,j} a_i b_j e_i \otimes f_j$$

is a linear combination of the tensors $e_i \otimes f_j$. Since every tensor can be written as a sum of elementary tensors, the elements $e_i \otimes f_j$ span $V \otimes W$.

Now, we must show that this spanning set is linearly independent. Suppose that $\sum_{i,j} c_{ij} e_i \otimes f_j = 0$, where all but finitely many c_{ij} are 0. We want to show that $c_{ij} = 0$ for every $i \in I, j \in J$. Fix two elements $i_0 \in I$ and $j_0 \in J$. To show that $c_{i_0 j_0} = 0$, consider the K -balanced map

$$\begin{aligned} V \times W &\rightarrow K \\ (v, w) &\mapsto a_{i_0} b_{j_0} \end{aligned}$$

where $v = \sum_i a_i e_i$ and $w = \sum_j b_j f_j$. By the universal property of tensor products, there is a linear map $f_0: V \otimes W \rightarrow K$ such that $f_0(v \otimes w) = a_{i_0} b_{j_0}$ on any elementary tensor $v \otimes w$. In particular, $f_0(e_{i_0} \otimes f_{j_0}) = 1$ and $f_0(e_i \otimes f_j) = 0$ for $(i, j) \neq (i_0, j_0)$. Applying f_0 to our assumption that $\sum_{i,j} c_{ij} e_i \otimes f_j = 0$ in $V \otimes W$ tells us that $c_{i_0 j_0} = 0$ in K . \square

Proposition 1.53. There are natural isomorphisms

1. $(U \otimes V) \otimes W \cong U \otimes (V \otimes W)$
2. $(U \oplus V) \otimes W \cong (U \otimes W) \oplus (V \otimes W)$.

Proof. (1.) For each fixed $w \in W$, the mapping $(u, v) \mapsto u \otimes (v \otimes w)$ is K -balanced, so by Theorem 1.51 there is a unique linear map from $U \otimes V$ to $U \otimes (V \otimes W)$ with $u \otimes v \mapsto u \otimes (v \otimes w)$. This shows that the map from $(U \otimes V) \times W$ to $U \otimes (V \otimes W)$ given by $(u \otimes v, w) \mapsto u \otimes (v \otimes w)$ is well defined. This map is also K -balanced, and thus another application of Theorem 1.51 shows that it induces a linear map $(U \otimes V) \otimes W \rightarrow$

$U \otimes (V \otimes W)$ such that $(u \otimes v) \otimes w \mapsto u \otimes (v \otimes w)$. In a similar manner, we can construct a map $U \otimes (V \otimes W) \rightarrow (U \otimes V) \otimes W$ with $u \otimes (v \otimes w) \mapsto (u \otimes v) \otimes w$ which is inverse to our first map. This proves the isomorphism.

(2.) The map $(U \oplus V) \times W \rightarrow (U \oplus W) \otimes (V \oplus W)$ defined by $((u, v), w) \mapsto (u \otimes w, v \otimes w)$ is clearly K -balanced. Thus it induces a linear map $f: (U \oplus V) \otimes W \rightarrow (U \otimes W) \oplus (V \otimes W)$ with

$$f((u, v) \otimes w) = (u \otimes w, v \otimes w).$$

In the other direction, we use the K -balanced maps $U \times W \rightarrow (U \oplus V) \otimes W$ and $V \times W \rightarrow (U \oplus V) \otimes W$ given by $(u, w) \mapsto (u, 0) \otimes w$ and $(v, w) \mapsto (0, v) \otimes w$ to obtain linear maps from $U \otimes W$ and $V \otimes W$ to $(U \oplus V) \otimes W$. Together these maps give a linear transformation g from the direct sum $(U \otimes W) \oplus (V \otimes W)$ to $(U \oplus V) \otimes W$ with

$$g(u \otimes w_1, v \otimes w_2) = (u, 0) \otimes w_1 + (0, v) \otimes w_2.$$

It is straightforward to see that f and g are inverse linear transformations, and the isomorphism holds. \square

Now let V and W be two representations of G .

Definition 1.54. We can define a representation of G on $V \otimes W$ called the **tensor product representation**. We let

$$\rho_{V \otimes W}(g): V \otimes W \rightarrow V \otimes W$$

be the linear map given by

$$\rho_{V \otimes W}(g): a_i \otimes b_j \mapsto \rho_V(g)(a_i) \otimes \rho_W(g)(b_j).$$

Suppose $\rho_V(g)$ is described by the matrix M and $\rho_W(g)$ is described by the matrix N in the given bases $\{a_1, \dots, a_n\}$ for V and $\{b_1, \dots, b_m\}$ for W . Then

$$\begin{aligned} \rho_{V \otimes W}(g): a_i \otimes b_t &\mapsto \left(\sum_{j=1}^n M_{ji} a_j \right) \otimes \left(\sum_{s=1}^m N_{st} b_s \right) \\ &= \sum_{\substack{j \in [1, n] \\ s \in [1, m]}} M_{ji} N_{st} a_j \otimes b_s. \end{aligned}$$

So $\rho_{V \otimes W}$ is described by the $nm \times nm$ matrix $M \otimes N$ whose entries are

$$[M \otimes N]_{js, it} = M_{ji} N_{st}.$$

This matrix has nm rows, and to specify a row we need a pair of numbers (j, s) where $j \in \{1, \dots, n\}$ and $s \in \{1, \dots, m\}$.

Proposition 1.55. $V \otimes W$ is isomorphic to $\text{Hom}(V^*, W)$.

Proof. Let $\{\alpha_1, \dots, \alpha_n\}$ be the basis for V^* dual to $\{a_1, \dots, a_n\}$. Then $\text{Hom}(V^*, W)$ has a basis given by $\{f_{it} | 1 \leq i \leq n, 1 \leq t \leq m\}$ where

$$f_{it}(\alpha_j) = \begin{cases} b_t & \text{if } j = i \\ 0 & \text{if } j \neq i \end{cases}$$

We obtain an isomorphism of vector spaces between $\text{Hom}(V^*, W)$ and $V \otimes W$ by the map

$$f_{it} \mapsto a_i \otimes b_t$$

extended to all of $\text{Hom}(V^*, W)$ by linearity. It remains to show that this isomorphism of vector spaces yields an isomorphism of representations. We can check this by showing that the representation $\rho_{\text{Hom}(V^*, W)}$ agrees with the definition of $\rho_{V \otimes W}$ when we write it in the basis $\{f_{it}\}$. Fix $g \in G$, and let M and N denote the matrices which describe $\rho_V(g)$ and $\rho_W(g)$ in the given bases. By definition,

$$\rho_{\text{Hom}(V^*, W)}(g): f_{it} \mapsto \rho_W(g) \circ f_{it} \circ \rho_{V^*}(g^{-1}).$$

Now $\rho_{V^*}(g^{-1})$ is given by the matrix M^T in the dual basis (CITE ME!!!), so

$$\rho_{V^*}(g^{-1}): \alpha_k \mapsto \sum_{j=1}^n M_{kj} \alpha_j.$$

Then

$$f_{it} \circ \rho_{V^*}(g^{-1}): \alpha_k \mapsto M_{ki} b_t$$

which means that

$$\rho_W(g) \circ f_{it} \circ \rho_{V^*}(g^{-1}): \alpha_k \mapsto M_{ki} \left(\sum_{s=1}^m N_{st} b_s \right).$$

Thus, if we write $\rho_W(g) \circ f_{it} \circ \rho_{V^*}(g^{-1})$ in terms of the basis $\{f_{js}\}$, we have

$$\rho_W(g) \circ f_{it} \circ \rho_{V^*}(g^{-1}) = \sum_{\substack{j \in [1, n] \\ s \in [1, m]}} M_{ji} N_{st} f_{js}$$

(since both sides agree on every basis vector α_k) and this is precisely the formula for the tensor product representation $\rho_{V \otimes W}$. \square

1.10 Character Theory

Definition 1.56. The **character** of a representation $\rho: G \rightarrow GL(V)$ is the function $\chi_V: G \rightarrow \mathbb{C}$ defined by $\chi_V(g) = \text{Tr}(\rho(g))$.

Note. The character of a representation is not a homomorphism in general, since $\text{Tr}(MN) \neq \text{Tr}(M)\text{Tr}(N)$ in general.

Proposition 1.57. (*Basic Properties*)

1. χ_V is conjugation invariant: $\chi_V(hgh^{-1}) = \chi_V(g)$ for all $g, h \in G$.
2. $\chi_V(1) = \dim V$.
3. $\chi_V(g^{-1}) = \overline{\chi_V(g)}$ for all $g \in G$.

Proof. 1. $\chi_V(hgh^{-1}) = \text{Tr}(hgh^{-1}) = \text{Tr}(ghh^{-1}) = \text{Tr}(g) = \chi_V(g)$ for any $g, h \in G$.

2. $\chi_V(1) = \text{Tr}(\text{Id}_V) = \dim V$.

3. Since G is finite, we have seen that $\rho(g)$ is a diagonal matrix with roots of unity along the diagonal with the right choice of basis. The inverse of a root of unity is given by its complex conjugate, so under this same basis, $\rho(g)^{-1}$ is clearly given by $\overline{\rho(g)}$. Thus, $\chi_V(g^{-1}) = \text{Tr}(\rho(g^{-1})) = \text{Tr}(\rho(g)^{-1}) = \text{Tr}(\overline{\rho(g)}) = \overline{\text{Tr}(\rho(g))} = \overline{\chi_V(g)}$. \square

Definition 1.58. A **class function** on G is a function on G whose values are invariant by conjugation of elements in G . The value of a class function at an element $g \in G$ depends only on the conjugacy class of g . We may therefore view class functions as functions on the set of conjugacy classes of G .

Note. The character χ_V of a representation V of G is a class function on G .

Proposition 1.59. *Isomorphic representations have the same character.*

Proof. We have seen (CITE ME!!!) that isomorphic representations can be described by the same set of matrices in the right choice of basis. \square

We will see later that the converse is true - if two representations have the same character, then they are isomorphic.

Proposition 1.60. *Let $\rho_V: G \rightarrow GL(V)$ and $\rho_W: G \rightarrow GL(W)$ be representations of G with characters χ_V and χ_W .*

1. $\chi_{V \oplus W} = \chi_V + \chi_W$.
2. $\chi_{V \otimes W} = \chi_V \cdot \chi_W$.

Proof. 1. Pick bases for V and W , so that $\rho_V(g)$ and $\rho_W(g)$ are described by matrices M and N . Then $\rho_{V \oplus W}(g)$ is described by the block-diagonal matrix

$$\begin{bmatrix} M & 0 \\ 0 & N \end{bmatrix}$$

So we have $\text{Tr}(\rho_{V \oplus W}(g)) = \text{Tr}(M) + \text{Tr}(N) = \text{Tr}(\rho_V(g)) + \text{Tr}(\rho_W(g))$.

2. $\rho_{V \otimes W}(g)$ is given by the matrix

$$[M \otimes N]_{js,it} = M_{ji}N_{st}$$

so

$$\begin{aligned} \text{Tr}(M \otimes N) &= \sum_{i,t} [M \otimes N]_{is,it} \\ &= \sum_{i,t} (M_{ii}N_{tt}) \\ &= \text{Tr}(M)\text{Tr}(N). \end{aligned}$$

Thus $\chi_{V \otimes W}(g) = \chi_V(g)\chi_W(g)$. \square

Proposition 1.61. 1. *Let $\{V_i\}$ be the irreducible representations of G , with d_i the dimension of V_i and χ_i the corresponding irreducible character. Then*

$$\chi_{\text{reg}} = d_1\chi_1 + \dots + d_r\chi_r$$

2.

$$\chi_{\text{reg}}(g) = \begin{cases} |G| & \text{if } g = e \\ 0 & \text{if } g \neq e \end{cases}$$

Definition 1.62. Let \mathbb{C}^G denote the set of all functions from G to \mathbb{C} . Then \mathbb{C}^G is a vector space with the sum of two functions defined pointwise and with scalar multiplication defined for $f \in \mathbb{C}^G, \lambda \in \mathbb{C}$ by

$$\begin{aligned} \lambda f &: G \rightarrow \mathbb{C} \\ g &\mapsto \lambda f(g). \end{aligned}$$

A basis for \mathbb{C}^G is clearly given by the set of functions

$$\{\delta_g | g \in G\}$$

defined by

$$\delta_g: h \mapsto \begin{cases} 1 & \text{if } h = g \\ 0 & \text{if } h \neq g \end{cases}$$

Definition 1.63. Let $\varphi, \psi \in \mathbb{C}^G$. We define an **inner product** on \mathbb{C}^G by

$$\langle \varphi | \psi \rangle = \frac{1}{|G|} \sum_{g \in G} \varphi(g) \overline{\psi(g)}.$$

It is easy to see that $\langle \varphi | \psi \rangle$ is linear in the first variable, conjugate-linear in the second variable (i.e., $\langle \varphi | \lambda \psi \rangle = \overline{\lambda} \langle \varphi | \psi \rangle$), and that $\langle \varphi | \psi \rangle = \overline{\langle \psi | \varphi \rangle}$. These three properties are the definition of a Hermitian inner product. Note that our basis elements δ_g are orthogonal with respect to this inner product, but not orthonormal since

$$\langle \delta_g | \delta_g \rangle = \begin{cases} \frac{1}{|G|} & \text{if } h = g \\ 0 & \text{if } h \neq g \end{cases}.$$

The characters of G are elements of \mathbb{C}^G , so we can evaluate this inner product on pairs of characters. The answer turns out to be very useful, but before we can begin the proof we require two quick lemmas:

Lemma 1.64. Let V be a vector space with subspace $U \subset V$, and let $\pi: V \rightarrow V$ be a projection onto U . Then

$$\text{Tr}(\pi) = \dim U.$$

Proof. Recall that $V = U \oplus \text{Ker}(\pi)$. (FROM WHENCE IS THIS RECOLLECTION?? MASCHKE??) If we fix bases for U and $\text{Ker}(\pi)$, which together give a basis for V , then π is given by the block-diagonal matrix

$$\begin{bmatrix} \mathbf{1} & 0 \\ 0 & \mathbf{0} \end{bmatrix}$$

where $\dim U$ is the size of the upper left block and $\dim \text{Ker}(\pi)$ is the size of the bottom right block. So $\text{Tr}(\pi) = \text{Tr}(\mathbf{1}_U) = \dim U$. \square

Lemma 1.65. Let $\rho: G \rightarrow GL(V)$ be any representation. Consider the linear map

$$\begin{aligned}\Psi: V &\rightarrow V \\ x &\mapsto \frac{1}{|G|} \sum_{g \in G} \rho(g)(x).\end{aligned}$$

Then Ψ is a projection from V onto the invariant subspace V^G .

Proof. We need to check that $\Psi(x) \in V^G$ for all $x \in V$. For any $h \in G$,

$$\begin{aligned}\rho(h)(\Psi(x)) &= \frac{1}{|G|} \sum_{g \in G} \rho(h)\rho(g)(x) \\ &= \frac{1}{|G|} \sum_{g \in G} \rho(hg)(x) \\ &= \frac{1}{|G|} \sum_{g \in G} \rho(g)(x) \quad (\text{by relabelling } g \mapsto h^{-1}g) \\ &= \Psi(x).\end{aligned}$$

Thus Ψ is a linear map $V \rightarrow V^G$. Next we need to check that Ψ is a projection. Let $x \in V^G$. Then

$$\begin{aligned}\Psi(x) &= \frac{1}{|G|} \sum_{g \in G} \rho(g)(x) \\ &= \frac{1}{|G|} \sum_{g \in G} x = x.\end{aligned}$$

□

Theorem 1.66. Let $\rho_V: G \rightarrow GL(V)$ and $\rho_W: G \rightarrow GL(W)$ be representations of G , and let χ_V, χ_W be their characters. Then

$$\langle \chi_W | \chi_V \rangle = \dim \operatorname{Hom}_G(V, W).$$

In particular, the inner product of two characters is always a non-negative integer. (Whereas in general, the inner product of two arbitrary functions can be any complex number.)

Proof. We have seen in Proposition 1.35 that

$$\operatorname{Hom}_G(V, W) \subset \operatorname{Hom}(V, W)$$

as the invariant subrepresentation, and by the previous lemma we have a projection

$$\begin{aligned}\Psi: \operatorname{Hom}(V, W) &\rightarrow \operatorname{Hom}(V, W) \\ f &\mapsto \frac{1}{|G|} \sum_{g \in G} \rho_{\operatorname{Hom}(V, W)}(g)(f).\end{aligned}$$

We claim that

$$\operatorname{Tr}(\Psi) = \langle \chi_W | \chi_V \rangle.$$

Once this claim is established, then Lemma 1.64 will prove the theorem. We proceed by calculating $\text{Tr}(\Psi)$. Fix bases $\{a_1, \dots, a_n\}$ for V and $\{b_1, \dots, b_m\}$ for W . Then $\text{Hom}(V, W)$ has an associated basis

$$\{f_{ji} | 1 \leq i \leq n, 1 \leq j \leq m\}$$

where

$$f_{ji}(a_i) = \begin{cases} b_j & \text{if } i = j \\ 0 & \text{if } i \neq j. \end{cases}$$

We may calculate $\text{Tr}(\Psi)$ as follows: For each i, j , compute the expression of $\Psi(f_{ji})$ in this basis, and take the coefficient of the basis element f_{ji} . This is a diagonal entry in the matrix for Ψ . Summing these values over all i and j will give us $\text{Tr}(\Psi)$.

Let $\widetilde{\rho}_V, \widetilde{\rho}_W$ be the matrix representations obtained by writing ρ_V and ρ_W in the given bases. We know that

$$\text{Hom}(V, W) = V^* \otimes W$$

so if we write $\rho_{\text{Hom}(V, W)}$ in the basis $\{f_{ji}\}$ then we get the tensor product of $\widetilde{\rho}_{V^*}$ and $\widetilde{\rho}_W$. Thus

$$\begin{aligned} \rho_{\text{Hom}(V, W)}(g)(f_{ji}) &= \rho_W(g) \circ f_{ji} \circ \rho_V(g^{-1}) \\ &= \sum_{\substack{k \in [1, n] \\ t \in [1, m]}} \widetilde{\rho}_V(g^{-1})_{ik} \widetilde{\rho}_W(g)_{tj} f_{kt}. \quad \text{Show another step?} \end{aligned}$$

Then

$$\begin{aligned} \Psi(f_{ji}) &= \frac{1}{|G|} \sum_{g \in G} \rho_{\text{Hom}(V, W)}(g)(f_{ji}) \\ &= \frac{1}{|G|} \sum_{g \in G} \sum_{\substack{k \in [1, n] \\ t \in [1, m]}} \widetilde{\rho}_V(g^{-1})_{ik} \widetilde{\rho}_W(g)_{tj} f_{kt}. \end{aligned}$$

The coefficient of f_{ji} in this expression is

$$\frac{1}{|G|} \sum_{g \in G} \widetilde{\rho}_V(g^{-1})_{ii} \widetilde{\rho}_W(g)_{jj}.$$

Therefore

$$\begin{aligned}
 \text{Tr}(\Psi) &= \sum_{\substack{k \in [1, n] \\ t \in [1, m]}} \frac{1}{|G|} \sum_{g \in G} \widetilde{\rho}_V(g^{-1})_{ii} \widetilde{\rho}_W(g)_{jj} \\
 &= \frac{1}{|G|} \sum_{g \in G} \left(\sum_{i=1}^n \widetilde{\rho}_V(g^{-1})_{ii} \right) \left(\sum_{j=1}^m \widetilde{\rho}_W(g)_{jj} \right) \\
 &= \frac{1}{|G|} \sum_{g \in G} \chi_V(g^{-1}) \chi_W(g) \\
 &= \frac{1}{|G|} \sum_{g \in G} \chi_W(g) \overline{\chi_V}(g) \quad (\text{by Proposition 3}) \\
 &= \langle \chi_W | \chi_V \rangle.
 \end{aligned}$$

□

Corollary 1.67. Let χ_1, \dots, χ_r be the irreducible characters of G . Then

$$\langle \chi_i | \chi_j \rangle = \begin{cases} 1 & \text{if } i = j \\ 0 & \text{if } i \neq j \end{cases}$$

Proof. Let χ_i and χ_j be the characters of the irreducible representations U_i, U_j . Then by Proposition 1.45,

$$\langle \chi_i | \chi_j \rangle = \dim \text{Hom}_G(U_i, U_j) = \begin{cases} 1 & \text{if } U_i, U_j \text{ are isomorphic} \\ 0 & \text{if } U_i, U_j \text{ are not isomorphic.} \end{cases}$$

□

Corollary 1.68. Let χ be any character of G . Then χ is irreducible if and only if

$$\langle \chi | \chi \rangle = 1$$

Proof. Write χ as a linear combination of irreducible characters

$$\chi = m_1 \chi_1 + \dots + m_k \chi_k$$

where each m_i is a non-negative integer. Then by Lemma 1.67,

$$\begin{aligned}
 \langle \chi | \chi \rangle &= \sum_{i, j \in [1, k]} m_i m_j \langle \chi_i | \chi_j \rangle \\
 &= m_1^2 + \dots + m_k^2.
 \end{aligned}$$

So $\langle \chi | \chi \rangle = 1$ if and only if exactly one of the $m_i = 1$ and the rest are 0. □

Corollary 1.69. Let $\rho_V: G \rightarrow GL(V)$ and $\rho_W: G \rightarrow GL(W)$ be representations of G . Then V and W are isomorphic if and only if $\chi_V = \chi_W$.

Proof. We have already seen that isomorphic representations have the same character by Proposition . On the other hand, suppose $\chi_V = \chi_W$. Let U_1, \dots, U_r be the irreducible

representations of G , and let χ_1, \dots, χ_r be their characters. We can write

$$V = U_1^{m_1} \oplus \dots \oplus U_r^{m_r}$$

for some non-negative integers m_1, \dots, m_r , and

$$W = U_1^{l_1} \oplus \dots \oplus U_r^{l_r}$$

for some non-negative integers l_1, \dots, l_r . So

$$\chi_V = m_1\chi_1 + \dots + m_r\chi_r$$

and

$$\chi_W = l_1\chi_1 + \dots + l_r\chi_r$$

. Thus we have

$$m_i = \langle \chi_V | \chi_i \rangle = \langle \chi_W | \chi_i \rangle = l_i$$

for all $i \in \{1, \dots, r\}$ since $\chi_V = \chi_W$. This proves V and W are isomorphic. \square

[6] [4] [1] [2] [5] [3]

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