

UNIVERSITY OF MISSOURI

MASTER'S PROJECT

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# 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  $\varphi: G \times X \rightarrow X$  (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  $\sigma_g$  from  $X$  into  $X$  defined by  $\sigma_g(x) = g \cdot x$  is a permutation of the set  $X$ , i.e.  $\sigma_g \in S_X$ .

*Proof.* We show that  $\sigma_g$  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

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

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  $\sigma_g$  is a permutation of  $X$ .  $\square$

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

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

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

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

**Proposition 1.4.** *Any homomorphism  $\psi$  from the group  $G$  into the symmetric group on  $S_X$  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  $\psi$  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  $X$ :

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

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

**Proposition 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, let  $F$  be a field, and let  $V$  be a vector space over  $F$ . A **linear representation** of  $G$  is any group homomorphism  $\varphi: G \rightarrow GL(V)$ .

**Definition 1.7.** 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 action of  $G$  on  $V$  which preserves the linear structure of  $V$ , that is,

$$g \cdot (v_1 + v_2) = g \cdot v_1 + g \cdot v_2 \quad \forall g \in G, v_1, v_2 \in V \quad (1.7.1)$$

$$g \cdot (kv) = k(g \cdot v) \quad \forall g \in G, v \in V, k \in F \quad (1.7.2)$$

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

**Proposition 1.8.** *The definitions of a linear representation given in 1.6 and 1.7 above are equivalent.*

*Proof.*  $(\rightarrow)$  Suppose that we have a homomorphism  $\varphi: G \rightarrow GL(V)$ . 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  $g \cdot v = \varphi(g)(v)$ . We check that this action preserves the linear structure of  $V$ .



**1.7.1** For any  $g \in G, v_1, v_2 \in V$  we have  $g \cdot (v_1 + v_2) = \varphi(g)(v_1 + v_2) = \varphi(g)(v_1) + \varphi(g)(v_2) = g \cdot v_1 + g \cdot v_2$ .

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

- ( $\leftarrow$ ) Suppose that we have an action of  $G$  on  $V$  which preserves the linear structure of  $V$  in the sense of Definition 1.7. We can apply Proposition 1.3 to obtain a homomorphism  $\varphi: G \rightarrow S_V$  given by  $\varphi(g) = \sigma_g$  where  $\sigma_g(v) = g \cdot v$ . It remains to show that the image  $\varphi(G)$  of  $G$  under  $\varphi$  is actually contained in  $GL(V)$ , i.e. that for each  $g \in G$  the map  $\sigma_g$  is linear. Fix an element  $g \in G$ . For any  $k \in F$  and  $v \in V$  we have

$$\begin{aligned} \sigma_g(kv) &= g \cdot (kv) && \text{(by definition of } \sigma_g) \\ &= k(g \cdot v) && \text{(by property 1.7.1)} \\ &= k(\sigma_g(v)) && \text{(by definition of } \sigma_g). \end{aligned}$$

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

$$\begin{aligned} \sigma_g(v_1 + v_2) &= g \cdot (v_1 + v_2) && \text{(by definition of } \sigma_g) \\ &= g \cdot v_1 + g \cdot v_2 && \text{(by property 1.7.2)} \\ &= \sigma_g(v_1) + \sigma_g(v_2) && \text{(by definition of } \sigma_g). \end{aligned}$$

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

**Definition 1.9.** Let  $G$  be a group, let  $F$  be a field, let  $V$  be a vector space over  $F$ , and let  $\varphi: G \rightarrow GL(V)$  be a representation of  $G$ . The **dimension** of the representation is the dimension of  $V$  over  $F$ .

- Example 1.10.** 1. Let  $V$  be a 1-dimensional vector space over the field  $F$ . The map  $\varphi: G \rightarrow GL(V)$  defined by  $\varphi(g) = 1$  for all  $g \in G$  is a representation called the *trivial representation* of  $G$ . The trivial representation has dimension 1.
2. If a finite group  $G$  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  $g \cdot e_x = e_{gx}$  for all  $x \in X$  and  $g \in G$ . Note that  $G$  permutes the basis elements of  $V$ .
3. A fundamental special case of a permutation representation is given by a finite group acting 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 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  $\varphi: S_n \rightarrow GL(\mathbb{C}) = \mathbb{C}^\times$  defined by  $\varphi(\sigma) = \text{sgn}(\sigma)$ . More generally, for any group  $G$  with a subgroup  $H$  of index 2, we can define an *alternating representation*  $\varphi: G \rightarrow GL(\mathbb{C})$  by letting  $\varphi(g) = 1$  if  $g \in H$  and  $\varphi(g) = -1$  if  $g \notin H$ . (We recover our original example by taking  $G = S_n$  and  $H = A_n$ .)

**Definition 1.11.** A **homomorphism** between two representations  $\varphi_1: G \rightarrow GL(V)$  and  $\varphi_2: G \rightarrow GL(W)$  is a linear map  $\psi: V \rightarrow W$  that intertwines with (respects) the  $G$ -action, i.e. such that

$$\psi(\varphi_1(g)(v)) = \varphi_2(g)(\psi(v)) \quad \forall v \in V, g \in G$$

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

*Note.* If we have representations  $(\varphi_1, V)$  and  $(\varphi_2, W)$  and an isomorphism of vector spaces  $\psi: V \rightarrow W$  then we can rewrite the compatibility requirement above as  $\varphi_2(g) = \psi \circ \varphi_1(g) \circ \psi^{-1}$  for all  $g \in G$ .

Given any representation  $(\varphi, V)$  of  $G$  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  $\psi: V \rightarrow F^n$ . We obtain a representation  $\phi$  of  $G$  on  $F^n$  by defining  $\phi = \psi \circ \varphi(g) \circ \psi^{-1}$  for all  $g \in G$ . Clearly, this representation is isomorphic to the original representation  $(\varphi, V)$ . In particular 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  $\varphi: G \rightarrow GL_n(F)$  and  $\phi: G \rightarrow GL_m(F)$  given by  $\varphi(g) = X_g$  and  $\phi(g) = Y_g$ . 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  $\varphi: G \rightarrow GL_n(F)$  and  $\phi: G \rightarrow GL_n(F)$  are isomorphic if and only if there exists  $A \in GL_n(F)$  such that  $\varphi(g) = A\phi(g)A^{-1}$  for all  $g \in G$ . This establishes the following proposition:

**Proposition 1.12.** *The isomorphism classes of  $n$ -dimensional representations of  $G$  on  $\mathbb{C}$  are in bijection with the quotient  $Hom(G; GL_n(\mathbb{C}))/GL_n(\mathbb{C})$  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 1.13** (Representations of  $\mathbb{Z}$ ). We want to classify all representations of the group  $\mathbb{Z}$  under addition. Consider an  $n$ -dimensional representation  $\varphi: \mathbb{Z} \rightarrow GL_n$ . For  $\varphi$  to be a group homomorphism requires that  $\varphi(0) = \text{Id}$ . Observe that for any  $0 \neq n \in \mathbb{Z}$ , we have  $\varphi(n) = \varphi(1 + \dots + 1) = \varphi(1)^n$ . Thus  $\varphi$  is completely determined by the matrix  $\varphi(1) \in GL_n(\mathbb{C})$ , 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 1.14** (Representations of the cyclic group of order  $n$ ). We shall classify all representations of the cyclic group  $G = 1 = g^n, g, \dots, g^{n-1}$  of order  $n$ . Consider a representation  $\varphi: G \rightarrow GL(V)$ . As in the previous example, we know that  $\varphi(1) = \text{Id}$  and  $\varphi(g^k) = \varphi(g)^k$ . Thus our representation  $\varphi$  is determined completely by the linear transformation  $\varphi(g)$ . It will be helpful to fix a basis of  $V$  so that we may view  $\varphi(g)$  as a matrix  $A$ . Recall from linear algebra that there exists a basis in which  $\varphi(g)$  takes the *Jordan normal form*.

$$A = \begin{bmatrix} J_1 & 0 & \dots & 0 \\ 0 & J_2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & J_m \end{bmatrix}$$

where each *Jordan block*  $J_k$  takes 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  $I = A^n$  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 as  $J_k = \lambda \text{Id} + N$  where  $N$  is the Jordan block with  $\lambda = 0$ . Thus we have

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

*Lemma.* 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  $N = 0$ , and  $J_k = \lambda^n$  is a  $1 \times 1$  block. Thus  $\varphi(g)$  is a diagonal matrix with  $n$ th roots of unity as diagonal entries.

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

**Definition 1.15.** A **subrepresentation** of  $V$  is a  $G$ -invariant subspace  $W \subseteq V$ ; that is a subspace  $W \subseteq V$  with the property that  $\varphi(g)(w) \in W$  for all  $g \in G, w \in W$ . Note that  $W$  effects a representation of  $G$  under the action  $\varphi(g)|_W$ .

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  $g(v + W) = \varphi(g)(v) + W$ . We must that this action is well defined. If we choose another  $v' \in v + W$ , then  $v - v' \in W$  so that  $\varphi(g)(v - v') \in W$  since  $W$  is  $G$ -invariant. Thus, the cosets  $\varphi(g)(v) + W$  and  $\varphi(g)(v') + W$  agree and this action is indeed well defined.

**Definition 1.16.** 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  $g(v + W) = \varphi(g)(v) + W$ .

We 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 1.17.** 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**, with the action  $g(v_1, v_2) = (g \cdot v_1, g \cdot v_2)$ .

**Definition 1.18.** A representation is called **irreducible** if it contains no proper invariant subspaces. It is called **completely reducible** if it decomposes into a direct sum of irreducible subrepresentations.

**Example 1.19.** 1. Any irreducible representation is completely reducible.

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

**Theorem 1.20.** 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 [1, Theorem 5.1]. □

**Theorem 1.21.** Every complex representation of a finite abelian group is completely reducible, and every irreducible representation is 1-dimensional.

*Proof.* Take an arbitrary element  $g \in G$ . Since  $G$  is finite, we can find an integer  $n$  such that  $g^n = 1$  and  $\varphi(g)^n = Id$ . Hence the minimal polynomial of  $\varphi(g)$  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  $\varphi(g)$  factors into linear factors only over  $\mathbb{C}$  so that  $\varphi(g)$  is diagonalizable. We conclude that each  $\varphi(g)$  is (separately) diagonalizable since  $g \in G$  was arbitrary.

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

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

Thus the matrices  $\{\varphi(g)\}$  commute, so we can apply 1.20 to conclude that  $\{\varphi(g)\}$  are simultaneously diagonalizable. This basis  $\{e_1, \dots, e_k\}$  yields the decomposition  $V = \mathbb{C}e_1 \oplus \mathbb{C}e_2 \oplus \dots \oplus \mathbb{C}e_n$ . □

We recall the following definition from linear algebra:

**Definition 1.22.** 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 1.23.** A representation  $\varphi$  of  $G$  on a complex vector space  $V$  is said to be **unitary** if  $V$  has been equipped with a hermetian inner product  $\langle | \rangle$  which is preserved by the action of  $G$



# Bibliography

- [1] Keith Conrad. *The Minimal Polynomial and Some Applications*. <http://www.math.uconn.edu/~kconrad/blurbs/linmultialg/minpolyandappns.pdf>. Online; accessed 12 December 2015. 2014.