

Notes from a course* on

Representation Theory of Finite Groups

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1. Linear representations of groups

Definition 1.1 (Linear representation): Let G be a finite group, and let V be a vector space. A linear representation (σ, V) of G is a homomorphism

$$\sigma : G \rightarrow \mathrm{GL}(V).$$

Example 1.1.1: The *trivial* representation of G is defined by $g \mapsto \mathrm{id}_V$.

Example 1.1.2: Consider a vector space V of dimension $\mathrm{ord}(G)$, and pick a basis $\{e_h\}_{h \in G}$. The *regular* representation $\tau : G \rightarrow \mathrm{GL}(V)$ of G is defined as follows: $\tau(g)$ sends each of the basis vectors $e_h \mapsto e_{gh}$.

The following propositions show that it is possible to define group representations in terms of a special class of group actions of G on the vector space V .

Proposition 1.2: Let G be a finite group, and let V be a vector space. Let $\rho : G \times V \rightarrow V$ be a group action of G on V , such that each for each G , the map $v \mapsto \rho(g, v)$ is linear. Then, (σ, V) is a linear representation, where

$$\sigma : G \rightarrow \mathrm{GL}(V), \quad g \mapsto (v \mapsto \rho(g, v)).$$

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Proposition 1.3: Let (σ, V) be a linear representation. Then, the map

$$\rho : G \times V \rightarrow V, \quad (g, v) \mapsto \sigma(g)(v)$$

is a group action of G on V , where for each $g \in G$, the map $v \mapsto \rho(g, v)$ is linear.

In this discussion, we will always work with finite groups, as well as finite dimensional vector spaces over a base field K . Typically, we will consider $K = \mathbb{C}$.

We will often abbreviate (σ, V) with V , and $\sigma(g)$ with g when the presence of σ is clear from context.

Definition 1.4: The dimension of a representation (σ, V) is $\dim(V)$.

Example 1.4.1: The only one dimensional representation of S_3 in \mathbb{C}^\times is the sign homomorphism. To see this, consider an arbitrary homomorphism $\sigma : S_3 \rightarrow \mathbb{C}^\times$. Note that $\ker(\sigma)$ must be a normal subgroup of S_3 , hence must be one of $\{e\}, A_3, S_3$. The third option yields the trivial representation $\sigma = \text{id}_{\mathbb{C}^\times}$, and the first option gives the contradiction $S_3 \cong \text{im}(\sigma) \subset \mathbb{C}^\times$ (the right side is abelian while the left is not). This leaves $\ker(\sigma) = A_3$, i.e. $\sigma(g) = 1$ for all even permutations $g \in S_3$. The remaining elements of S_3 (the odd permutations) must be sent to -1 , since for any odd permutation $h \in S_3$, the permutation h^2 is even, so $\sigma(h)^2 = \sigma(h^2) = 1$. The result is precisely the sign homomorphism

$$\sigma : S_3 \rightarrow \mathbb{C}^\times, \quad g \mapsto \begin{cases} +1 & \text{if } g \in A_3 \\ -1 & \text{if } g \notin A_3. \end{cases}$$

Example 1.4.2: Construct an equilateral triangle in \mathbb{C}^2 centered at the origin, and consider the natural action of S_3 on it (permuting its vertices v_1, v_2, v_3). This induces a two dimensional representation $\sigma : S_3 \rightarrow \text{GL}(\mathbb{C}^2)$. Note that $\{v_1, v_2\}$ forms a basis of \mathbb{C}^2 ; the third vertex can be obtained via $v_3 = -v_1 - v_2$. With this, we can calculate the image of (v_1, v_2) under the action of each $g \in S_3$, and hence the matrices of $\sigma(g)$ in the given basis as follows.

g	$(\sigma(g)(v_1), \sigma(g)(v_2))$	Matrix of $\sigma(g)$
e	(v_1, v_2)	$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$
(12)	(v_2, v_1)	$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$
(23)	$(v_1, v_3) = (v_1, -v_1 - v_2)$	$\begin{bmatrix} 1 & -1 \\ 0 & -1 \end{bmatrix}$
(31)	$(v_3, v_2) = (-v_1 - v_2, v_2)$	$\begin{bmatrix} -1 & 0 \\ -1 & 1 \end{bmatrix}$
(123)	$(v_2, v_3) = (v_2, -v_1 - v_2)$	$\begin{bmatrix} 0 & -1 \\ 1 & -1 \end{bmatrix}$

(321)

$$(v_3, v_1) = (-v_1 - v_2, v_1)$$

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

Consider the setting $K = \mathbb{C}$. The fact that G is a finite group means that each element $g \in G$ has finite order, hence satisfies $g^m = 1$ for some $m \mid \text{ord}(G)$. This means that $\sigma(g)^m = \text{id}_V$, whence $x^m - 1$ is an annihilating polynomial for $\sigma(g)$. A consequence of this is that the minimal polynomial of $\sigma(g)$ is a factor of $x^m - 1$; but the latter splits into distinct linear factors. Furthermore, all eigenvalues of $\sigma(g)$ are roots of its minimal polynomial. This yields the following result.

Proposition 1.5: Suppose that $K = \mathbb{C}$. Let (σ, V) be a representation of G , and let $g \in G$. Then, $\sigma(g)$ is diagonalizable, and its eigenvalues are roots of unity.

2. Subrepresentations

Definition 2.1 (Stable subspace): Let (σ, V) be a representation of G , and let $W \subseteq V$ be a subspace of V . We say that W is a stable subspace of V if it is invariant under the action of G , i.e. $gw \in W$ for all $g \in G, w \in W$.

Example 2.1.1: Let S_3 act on \mathbb{C}^3 by permuting the basis vectors $\{e_1, e_2, e_3\}$. Then, the subspace $\text{span}\{e_1 + e_2 + e_3\}$ is stable.

Definition 2.2 (Subrepresentation): Let W be a stable subspace of V . We say that (σ, W) is a subrepresentation of (σ, V) .

Theorem 2.3: Suppose that $\text{char}(K) \nmid \text{ord}(G)$. Let W be a stable subspace of V . Then, there exists a stable subspace W' of V such that $V = W \oplus W'$.

When working with the field $K = \mathbb{C}$, **Theorem 2.3** admits a simpler form by invoking the orthocomplement of $W \subseteq V$, with respect to a suitable Hermitian form on V . We say that a Hermitian form $\langle \cdot, \cdot \rangle : V \times V \rightarrow \mathbb{C}$ is G -invariant if for all $g \in G, v, v' \in V$, we have $\langle gv, gv' \rangle = \langle v, v' \rangle$.

Theorem 2.4: Suppose that $K = \mathbb{C}$. If W is a stable subspace of V , then W^\perp is a stable subspace of V , with $V = W \oplus W^\perp$.

Remark: The subspace W^\perp is defined with respect to a non-degenerate G -invariant Hermitian form.

Proof: For all $g \in G, w \in W, w' \in W^\perp$, observe that $g^{-1}w \in W$, so

$$\langle gw', w \rangle = \langle gw', gg^{-1}w \rangle = \langle w', g^{-1}w \rangle = 0,$$

whence $gw' \in W^\perp$. □

Example 2.4.1: Continuing [Example 2.1.1](#), the subspace $\text{span}\{e_1 - e_2, e_2 - e_3, e_3 - e_1\}$ is also stable under the action of S_3 . This gives a two dimensional subrepresentation of S_3 . In fact, it is easy to check that the matrices describing this representation in the basis $\{2e_1 - e_2 - e_3, 2e_2 - e_3 - e_1\}$ are precisely the same as those in [Example 1.4.2](#), making these two representations identical in some sense.

Remark: Given any Hermitian form $\langle \cdot, \cdot \rangle : V \times V \rightarrow C$, we can obtain a G -invariant Hermitian form on V defined by

$$(u, v) \mapsto \sum_{g \in G} \langle gu, gv \rangle.$$

Returning to [Theorem 2.3](#), observe that if π_W is a projection onto the subspace W , then we may write $V = W \oplus \ker(\pi_W)$. With this in mind, we will construct the required subspace W' as the kernel of a suitable projection map $\pi_{W'}$. For this, we demand that $\pi_{W'}$ be G -invariant.

Definition 2.5: A linear map $f : V \rightarrow V'$ is called G -invariant if it is compatible with the G -action, i.e. for all $g \in G, v \in V$, we have $f(gv) = gf(v)$.

Note that the above definition implicitly deals with *two* representations (σ, V) and (σ', V') of G . The indicated property really looks like $\sigma'(g)(f(v)) = f(\sigma(g)(v))$ when written in full.

Lemma 2.6: Let $f : V \rightarrow V'$ be G -invariant. Then,

1. $\ker(f)$ is a stable subspace of V .
2. $\text{im}(f)$ is a stable subspace of V' .

Given any linear map $f : V \rightarrow V'$, we can construct a G -invariant linear map via

$$\tilde{f} : V \rightarrow V', \quad v \mapsto \sum_{g \in G} gf(g^{-1}v).$$

With this, we are ready to furnish a proof of our theorem.

Proof of Theorem 2.3: Let $\pi : V \rightarrow W$ be any projection onto W . Observe that

$$\pi_W : V \rightarrow W, \quad v \mapsto \frac{1}{\text{ord}(G)} \sum_{g \in G} g\pi(g^{-1}v)$$

is a G -invariant projection onto W . Setting $W' = \ker(\pi_W)$ completes the proof. \square

Remark: Note how the assumption that $\text{char}(K) \nmid \text{ord}(G)$ is crucial for defining the projection $\pi_{W'}$.

3. Irreducible representations

Definition 3.1 (Irreducible representations): We say that a representation is irreducible if it admits no proper non-trivial subrepresentations.

In other words, a representation (σ, V) is irreducible *if and only if* the only G -invariant subspaces of V are $\{0\}, V$.

Example 3.1.1: All one dimensional representations are irreducible.

Theorem 3.2 (Maschke's Theorem): Suppose that $\text{char}(K) \nmid \text{ord}(G)$. Then, every representation of G over the field K can be written as a direct sum of irreducible representations of G .

Proof: Follows immediately from [Theorem 2.3](#). □

Example 3.2.1: Combining [Examples 2.1.1](#) and [2.4.1](#), we have the decomposition

$$\mathbb{C}^3 = \text{span}\{e_1 + e_2 + e_3\} \oplus \text{span}\{e_1 - e_2, e_2 - e_3, e_3 - e_1\}$$

into irreducible subrepresentations of S_3 .

When we say that two representations (σ, V) and (σ', V') are isomorphic, denoted $V \cong V'$, we mean that there exists a G -invariant linear bijection $f : V \rightarrow V'$. The following result offers a very powerful characterization of G -invariant maps between irreducible representations.

Theorem 3.3 (Schur's Lemma): Let V, V' be two irreducible representations of G , and let $f : V \rightarrow V'$ be a G -invariant linear map.

1. If $V \not\cong V'$, then $f = 0$.
2. If $V = V'$ and K is algebraically closed, then f is a scalar map, i.e. $f = \lambda \text{id}_V$ for some $\lambda \in K$.

Proof:

1. Suppose that $f \neq 0$. It suffices to show that f is an isomorphism; to do so, we make extensive use of [Lemma 2.6](#).

First, $\ker(f) \subseteq V$ is stable, hence must be one of $\{0\}, V$ by the irreducibility of V . The assumption $f \neq 0$ forces $\ker(f) = \{0\}$, whence f is injective.

Next, $\text{im}(f) \subseteq V'$ is stable, hence must be one of $\{0\}, V'$ by the irreducibility of V' . Again, $f \neq 0$ forces $\text{im}(f) = V'$, whence f is surjective.

2. We have a G -invariant linear bijection $f : V \rightarrow V$; suppose that $f \neq 0$. Let λ be an eigenvalue of f , and observe that the map $(f - \lambda \text{id}_V)$ is also G -invariant; indeed, for all $g \in G, v \in V$,

$$(f - \lambda)(gv) = f(gv) - \lambda gv = gf(v) - g\lambda v = g(f - \lambda)(v).$$

Since λ is an eigenvalue of f , we have $\ker(f - \lambda) \neq \{0\}$. Since $\ker(f - \lambda) \subseteq V$ is stable and V is irreducible, we must have $\ker(f - \lambda) = V$, whence $f - \lambda \text{id}_V = 0$. □

Remark: Note how the existence of the scalar $\lambda \in K$ is guaranteed by the fact that K is algebraically closed.

Corollary 3.3.1: All \mathbb{C} -linear irreducible representations of finite abelian groups are one dimensional.

Proof: Let (σ, V) be an irreducible representation of a finite abelian group G . Check that for each $g \in G$, the linear map $\sigma(g) : V \rightarrow V$ is G -invariant, since it commutes with all $\sigma(h)$ for $h \in G$. From Schur's Lemma ([Theorem 3.3](#)), each $\sigma(g)$ is a scalar map. As a result, every one dimensional subspace of V is stable. The result now follows from the irreducibility of V . □

4. Characters

Definition 4.1 (Character): The character χ_V of a representation (σ, V) of G is the function

$$\chi_V : G \rightarrow K, \quad g \mapsto \text{tr}(\sigma(g)).$$

Example 4.1.1: $\chi_V(1) = \dim(V)$.

Observe that $\chi_V(g)$ is precisely the sum of eigenvalues of $\sigma(g)$. The eigenvalues of $\chi_V(g^{-1})$ are simply reciprocals of those of $\chi_V(g)$; in the setting $K = \mathbb{C}$, the following result is immediate from [Proposition 1.5](#).

Proposition 4.2: Suppose that $K = \mathbb{C}$. Then, $\chi_V(g^{-1}) = \overline{\chi_V(g)}$.

The fact that the trace is invariant under conjugation, i.e. $\text{tr}(tst^{-1}) = \text{tr}(s)$, yields the following result.

Lemma 4.3: χ_V is a class function, i.e. χ_V is constant on conjugacy classes of G .

Lemma 4.4: Isomorphic representations have the same character.

Proof: Let $f : V \rightarrow V'$ be an isomorphism of representations (σ, V) and (σ', V') of G . Then for each $g \in G$, we have $f \circ \sigma(g) = \sigma'(g) \circ f$, hence $\sigma(g) = f^{-1} \circ \sigma'(g) \circ f$. Taking the trace of both sides and using the cyclic property gives $\text{tr}(\sigma(g)) = \text{tr}(\sigma'(g))$ as desired. \square

The space K^G of all maps $G \rightarrow K$ forms a vector space over K , with dimension $\text{ord}(G)$. In the setting $K = \mathbb{C}$, we may define the following inner product.

$$\langle \cdot, \cdot \rangle : \mathbb{C}^G \times \mathbb{C}^G \rightarrow \mathbb{C}, \quad (\varphi, \psi) \mapsto \frac{1}{\text{ord}(G)} \sum_{g \in G} \varphi(g) \overline{\psi(g)}.$$

Remark: For characters χ, χ' , [Proposition 4.2](#) gives

$$\langle \chi, \chi' \rangle = \frac{1}{\text{ord}(G)} \sum_{g \in G} \chi(g) \chi'(g^{-1}).$$

Theorem 4.5 (Orthogonality of characters): Suppose that $K = \mathbb{C}$. Let (σ, V) , (σ', V') be two irreducible representations of G .

1. If $V \not\cong V'$, then $\langle \chi_V, \chi_{V'} \rangle = 0$.
2. If $V \cong V'$, then $\langle \chi_V, \chi_{V'} \rangle = 1$.

Proof: Let $\{v_1, \dots, v_n\}$ be a basis of V , and let $\{v'_1, \dots, v'_m\}$ be a basis of V' . Given any linear map $f : V \rightarrow V'$, we will denote $\tilde{f} = \sum_{g \in G} \sigma'(g) \circ f \circ \sigma(g)^{-1}$; recall that \tilde{f} is G -invariant.

1. Observe that Schur's Lemma ([Theorem 3.3](#)) forces all such $\tilde{f} = 0$. In particular, consider the maps e_{ij} defined for each $1 \leq i \leq n, 1 \leq j \leq m$ as

$$e_{ij} : V \rightarrow V', \quad \sum_i \alpha_i v_i \mapsto \alpha_i v'_j.$$

These maps $\{e_{ij}\}$ form a basis of $\mathcal{L}(V, V')$. Check that the matrix entries obey

$$[a \circ e_{ij} \circ b]_{k\ell} = [a]_{ki} [b]_{j\ell},$$

so using $\tilde{e}_{ij} = 0$ gives the relations

$$[\tilde{e}_{ij}]_{kl} = \sum_{g \in G} [\sigma'(g) \circ e_{ij} \circ \sigma(g)^{-1}]_{kl} = \sum_{g \in G} [\sigma'(g)]_{ki} [\sigma(g)^{-1}]_{j\ell} = 0$$

for all $1 \leq i, k \leq n, 1 \leq j, \ell \leq m$. These hold in particular for $i = k, j = \ell$; summing over $1 \leq i \leq n, 1 \leq j \leq m$, we have

$$\begin{aligned} 0 &= \sum_{ij} \sum_{g \in G} [\sigma'(g)]_{ii} [\sigma(g)^{-1}]_{jj} = \sum_{g \in G} \left(\left(\sum_i [\sigma'(g)]_{ii} \right) \left(\sum_j [\sigma(g)^{-1}]_{jj} \right) \right) \\ &= \sum_{g \in G} \chi_V(g) \chi_{V'}(g^{-1}) \\ &= \text{ord}(G) \langle \chi_V, \chi_{V'} \rangle. \end{aligned}$$

2. Schur's Lemma ([Theorem 3.3](#)) forces all such $\tilde{f} = \lambda_f \text{id}_V$ for scalars $\lambda_f \in \mathbb{C}$. To extract λ_f , take the trace of both sides to obtain

$$n\lambda_f = \dim(V)\lambda_f = \sum_{g \in G} \text{tr}(\sigma'(g) \circ f \circ \sigma(g)^{-1}) = \text{ord}(G) \text{tr}(f).$$

With this, each $\tilde{e}_{ij} = \lambda_{ij} \delta_{ij} \text{id}_V$, where $\lambda_{ij} = \text{ord}(G)/n$. Thus, we obtain the relations

$$\sum_{g \in G} [\sigma'(g)]_{ki} [\sigma(g)^{-1}]_{j\ell} = \frac{1}{n} \text{ord}(G) \delta_{ij} \delta_{kl}$$

for all $1 \leq i, j, k, \ell \leq n$. Following a similar process as before,

$$\begin{aligned} \text{ord}(G) \langle \chi_V, \chi_{V'} \rangle &= \sum_{g \in G} \left(\left(\sum_i [\sigma'(g)]_{ii} \right) \left(\sum_j [\sigma(g)^{-1}]_{jj} \right) \right) \\ &= \sum_{ij} \sum_{g \in G} [\sigma'(g)]_{ii} [\sigma(g)^{-1}]_{jj} \\ &= \sum_{ij} \frac{1}{n} \text{ord}(G) \delta_{ij} \\ &= \text{ord}(G) \end{aligned}$$

This completes the proof. □

With this, the characters of irreducible representations form an orthonormal subset of class functions on G . To check whether a representation V is irreducible or not, it is enough to verify that $\langle \chi_V, \chi_V \rangle = 1$.

Corollary 4.5.1: The number of irreducible representations of G (up to isomorphism) is at most the number of conjugacy classes of G .

Example 4.5.2: We have now established that the trivial representation, the one dimensional representation from [Example 1.4.1](#), and the two dimensional representation from [Example 1.4.2](#) are the only irreducible representations of S_3 . Note that S_3 has three conjugacy classes: $\{e\}$, $\{(12), (23), (31)\}$, and $\{(123), (321)\}$. With this, we can construct the *character table* for S_3 , with each row containing the characters of the group elements with respect to the given representation.

S_3	e	(12)	(23)	(31)	(123)	(321)
Trivial	1	1	1	1	1	1
Sign	1	-1	-1	-1	1	1
Standard	2	0	0	0	-1	-1

Observe that the rows of this table are orthogonal; indeed, so are the columns!

Given any representation V of G , we can use Maschke's Theorem ([Theorem 3.2](#)) to decompose it as a direct sum of (non-isomorphic) irreducible representations V_1, \dots, V_k , with multiplicities m_1, \dots, m_k . By representing the elements of G as matrices in block diagonal form, we can derive the following result.

Lemma 4.6: Let V_1, \dots, V_k be irreducible representations of G , and let

$$V \cong m_1 V_1 \oplus \dots \oplus m_k V_k.$$

Then,

$$\chi_V \cong m_1 \chi_{V_1} + \dots + m_k \chi_{V_k}.$$

The multiplicities can be recovered as $m_i = \langle \chi_V, \chi_{V_i} \rangle$.

This immediately tells us that $\chi_V = \chi_{V'}$ if and only if $V \cong V'$. Furthermore, we have the relation

$$\langle \chi_V, \chi_V \rangle = \sum_i m_i^2.$$

Example 4.6.1: Let S_4 act on \mathbb{C}^4 by permuting the basis vectors $\{e_1, e_2, e_3, e_4\}$, and let (σ, V) denote the induced (regular) representation. Note that each matrix $\sigma(g)$ is a permutation, hence its trace $\chi_{V(g)}$ is precisely the number of elements of $\{1, 2, 3, 4\}$ fixed by the action of g . With this, we can compute χ_V for each conjugacy class (identified by its cycle type) as follows.

S_4	e	$(ab) \times 6$	$(ab)(cd) \times 3$	$(abc) \times 8$	$(abcd) \times 6$
Trivial	1	1	1	1	1
Sign	1	-1	1	1	-1
V	4	2	0	1	0

Compute

$$\langle \chi_V, \chi_V \rangle = \frac{1}{24}(4^2 + 6 \cdot 2^2 + 8 \cdot 1^2) = 2,$$

whence V is not irreducible. Indeed, we know that $W_1 = \text{span}\{e_1 + e_2 + e_3 + e_4\}$ is a trivial subrepresentation of V of dimension 1. Furthermore, $2 = 1^2 + 1^2$ is the only way of writing 2 as a sum of squares of integers, so V must decompose into precisely two irreducible subrepresentations with both multiplicities 1. This means that $V \cong W_1 \oplus W_3$ for some irreducible representation W_3 of dimension 3. Using $\chi_V = \chi_{W_1} + \chi_{W_3}$, we can compute the character χ_{W_3} and obtain the following.

S_4	e	$(ab) \times 6$	$(ab)(cd) \times 3$	$(abc) \times 8$	$(abcd) \times 6$
W_3	3	1	-1	0	-1

Next, we move on to a different representation of S_4 : consider all subsets of size 2 of $\{1, 2, 3, 4\}$ (of which there are 6), and consider the action on this collection induced by the permutations on the set $\{1, 2, 3, 4\}$. Let (τ, V') denote the induced representation. Again, $\chi_{V'}(g)$ is the number of 2-subsets fixed by the action of g . For instance, an element $(ab) \in S_4$ will only fix 2-subsets $\{a, b\}, \{c, d\}$, while an element $(abc) \in S_4$ fixes no 2-subset. With this, we have the following.

S_4	e	$(ab) \times 6$	$(ab)(cd) \times 3$	$(abc) \times 8$	$(abcd) \times 6$
V'	6	2	2	0	0

Compute $\langle \chi_{V'}, \chi_{V'} \rangle = 3 = 1^2 + 1^2 + 1^2$. Again, we may compute $\langle \chi_{V'}, \chi_{W_1} \rangle = 1$ and $\langle \chi_{V'}, \chi_{W_3} \rangle = 1$, which tells us that $V' \cong W_1 \oplus W_3 \oplus W_2$ for some irreducible representation W_2 of dimension 2. Using $\chi_{V'} = \chi_{W_1} + \chi_{W_3} + \chi_{W_2}$, we can compute the character χ_{W_2} .

S_4	e	$(ab) \times 6$	$(ab)(cd) \times 3$	$(abc) \times 8$	$(abcd) \times 6$
W_2	2	0	2	-1	0

We now have 4 irreducible characters of S_4 ; indeed, we may combine W_3 with the sign representation to get another irreducible representation W'_3 , completing the character table of S_4 .

S_4	e	$(ab) \times 6$	$(ab)(cd) \times 3$	$(abc) \times 8$	$(abcd) \times 6$
Trivial	1	1	1	1	1
Sign	1	-1	1	1	-1
W_2	2	0	2	-1	0
W_3	3	1	-1	0	-1
W'_3	3	-1	-1	0	1

The last trick uses the following proposition.

Proposition 4.7: Let (σ, V) and $(\tau, \mathbb{C}^\times)$ be representations of G . Then, $(\tau\sigma, V)$ is also a representation of G , where $(\tau\sigma)(g) = \tau(g)\sigma(g)$. Furthermore, $\chi_{\tau\sigma} = \chi_\tau\chi_\sigma$.