

Representation Theory

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0 Introduction

Representaiton theory is the theory of how *groups* act as groups of linear transformations on *vector spaces*.

Here the groups are either *finite*, or *compact topological groups* (infinite), for example, $SU(n)$ and $O(n)$. The vector spaces we conside are finite dimensional, and usually over \mathbb{C} . Actions are *linear* (see below).

Some books: James-Liebeck (CUP); Alperin-Bell (Springer); Charles Thomas, *Representations of finite and Lie groups*; Onlne notes: SM, Teleman; P.Webb *A course in finite group representation theory* (CUP); Charlie Curtis, *Pioneers of representation theory* (history).

1 Group actions

Throughout this course, if not specified otherwise:

- F is a field, usually \mathbb{C} , \mathbb{R} or \mathbb{Q} . When the field is one of these, we are discussing *ordinary representation theory*. Sometimes $F = F_p$ or \bar{F}_p (algebraic closure, see Galois Theory), in which case the theory is called *modular representation theory*;
- V is a vector space over F , always finite dimensional;
 $GL(V) = \{\theta : V \rightarrow V, \theta \text{ linear, invertible}\}$, i.e. $\det \theta \neq 0$.

Recall from Linear Algebra:

If $\dim_F V = n < \infty$, choose basis e_1, \dots, e_n over F , so we can identify it with F^n . Then $\theta \in GL(V)$ corresponds to an $n \times n$ matrix $A_\theta = (a_{ij})$, where $\theta(e_j) = \sum_i a_{ij} e_i$. In fact, we have $A_\theta \in GL_n(F)$, the general linear group.

(1.1) $GL(V) \cong GL_n(F)$ as groups by $\theta \rightarrow A_\theta$ ($A_{\theta_1 \theta_2} = A_{\theta_1} A_{\theta_2}$ and bijection).
 Choosing different basis gives different isomorphism to $GL_n(F)$, but:

(1.2) Matrices A_1, A_2 represent the same element of $GL(V)$ w.r.t different bases iff they are conjugate (similar), i.e. $\exists X \in GL_n(F)$ s.t. $A_2 = X A_1 X^{-1}$.

Recall that $\text{tr}(A) = \sum_i a_{ii}$ where $A = (a_{ij})$, the *trace* of A .

(1.3) $\text{tr}(X A X^{-1}) = \text{tr}(A)$, hence we can define $\text{tr}(\theta) = \text{tr}(A_{\theta_1})$ independent of basis.

(1.4) Let $\alpha \in GL(V)$ where V in f.d. over \mathbb{C} , with $\alpha^m = \iota$ for some m (here ι is the identity map). Then α is diagonalisable.

Recall $\text{End} V$ is the set of all linear maps $V \rightarrow V$, e.g. $\text{End}(F^n) = M_n(F)$ some $n \times n$ matrices.

(1.5) *Proposition.* Take V f.d. over \mathbb{C} , $\alpha \in \text{End}(V)$. Then α is diagonalisable iff there exists a polynomial f with distinct linear factors with $f(\alpha) = 0$. For example, in (1.4), where $\alpha^m = \iota$, we take $f = X^m - 1 = \prod_{j=0}^{m-1} (X - \omega^j)$ where $\omega = e^{2\pi i/m}$ is the (m^{th}) root of unity. In fact we have:

(1.4)* A finite family of commuting separately diagonalisable automorphisms of a \mathbb{C} -vector space can be simultaneously diagonalised (useful in abelian groups).

Recall from Group Theory:

(1.6) The symmetric group, $S_n = \text{Sym}(X)$ on the set $X = \{1, \dots, n\}$ is the set of all permutations of X . $|S_n| = n!$. The alternating group A_n on X is the set of products of an even number of transpositions (2-cycles). $|A_n| = \frac{n!}{2}$.

(1.7) Cyclic groups of order m : $C_m = \langle x : x^m = 1 \rangle$. For example, $(\mathbb{Z}/m\mathbb{Z}, +)$; also, the group of m^{th} roots of unity in \mathbb{C} (inside $GL_1(\mathbb{C}) = \mathbb{C}^*$, the multiplicative group of \mathbb{C}). We also have the group of rotations, centre O of regular m -gon in \mathbb{R}^2 (inside $GL_2(\mathbb{R})$).

(1.8) Dihedral groups D_{2m} of order $2m = \langle x, y : x^m = y^2 = 1, yxy^{-1} = x^{-1} \rangle$. Think of this as the set of rotations and reflections preserving a regular m -gon.

(1.9) Quaternion group, $Q_8 = \langle x, y \mid x^4 = 1, y^2 = x^2, yxy^{-1} = x^{-1} \rangle$ of order 8. For example, in $GL_2(\mathbb{C})$, put $i = \begin{pmatrix} i & 0 \\ 0 & i \end{pmatrix}, j = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}, k = \begin{pmatrix} 0 & i \\ i & 0 \end{pmatrix}$, then $Q_8 = \{\pm I_2, \pm i, \pm j, \pm k\}$.

(1.10) The conjugacy class (ccls) of $g \in G$ is $\mathcal{C}_G(g) = \{xgx^{-1} : x \in G\}$. Then $|\mathcal{C}_G(g)| = |G : C_G(g)|$, where $C_G(g) = \{x \in G : xg = gx\}$, the centraliser of $g \in G$.

(1.11) Let G be a group, X be a set. G acts on X if there exists a map $\cdot : G \times X \rightarrow X$ by $(g, x) \rightarrow g \cdot x$ for $g \in G, x \in X$, s.t. $1 \cdot x = x$ for all $x \in X$, $(gh) \cdot x = g \cdot (h \cdot x)$ for all $g, h \in G, x \in X$.

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

Proof. For $g \in G$, the function $\theta_g : X \rightarrow X$ by $x \rightarrow gx$ is a permutation on X , with inverse $\theta_{g^{-1}}$. Moreover, $\forall g_1, g_2 \in G, \theta_{g_1 g_2} = \theta_{g_1} \theta_{g_2}$ since $(g_1 g_2)x = g_1(g_2 x)$ for $x \in X$. \square

2 Basic Definitions

2.1 Representations

Let G be finite, F be a field, usually \mathbb{C} .

Definition. (2.1)

Let V be a f.d. vector space over F . A (linear, in some books) *representation* of G on V is a group homomorphism

$$\rho = \rho_V : G \rightarrow GL(V)$$

Write ρ_g for the image $\rho_V(g)$; so for each $g \in G$, $\rho_g \in GL(V)$, and $\rho_{g_1 g_2} = \rho_{g_1} \rho_{g_2}$, and $(\rho_g)^{-1} = \rho_{g^{-1}}$.

The *dimension* (or *degree*) of ρ is $\dim_F V$.

(2.2) Recall $\ker \rho \triangleleft G$ (kernel is a normal subgroup), and $G/\ker \rho \cong \rho(G) \leq GL(V)$ (1st isomorphism theorem). We say ρ is *faithful* if $\ker \rho = 1$.

An alternative (and equivalent) approach is to observe that a representation of G on V is "the same as" a *linear action* of G :

Definition. (2.3)

G *acts linearly* on V if there exists a *linear action*

$$\begin{aligned} G \times V &\rightarrow V \\ (g, v) &\rightarrow gv \end{aligned}$$

By linear action we mean: (action) $(g_1 g_2)v = g_1(g_2 v)$, $1v = v \ \forall g_1, g_2 \in G, v \in V$, and (linear) $g(v_1 + v_2) = gv_1 + gv_2$, $g(\lambda v) = \lambda gv \ \forall g \in G, v_1, v_2 \in V, \lambda \in F$.

Now if G acts linearly on V , the map

$$\begin{aligned} G &\rightarrow GL(V) \\ g &\rightarrow \rho_g \end{aligned}$$

with $\rho_g : v \rightarrow gv$ is a representation of G . Conversely, given a representation $\rho : G \rightarrow GL(V)$, we have a linear action of G on V via $g \cdot v := \rho(g)v \ \forall v \in V, g \in G$.

(2.4) In (2.3) we also say that V is a G -space or that V is a G -module. In fact if we define the *group algebra* FG , or $F[G]$, to be $\{\sum \alpha_j g : \alpha_j \in F\}$ with natural addition and multiplication, then V is actually a FG -module (in the sense from GRM).

(2.5) R is a *matrix representation* of G of degree n if R is a homomorphism $G \rightarrow GL_n(F)$. Given representation $\rho : G \rightarrow GL(V)$ with $\dim_F V = n$, fix basis B ; we get matrix representation

$$\begin{aligned} G &\rightarrow GL_n(F) \\ g &\rightarrow [\rho(g)]_B \end{aligned}$$

Conversely, given matrix representation $R : G \rightarrow GL_n(F)$, we get representation

$$\begin{aligned}\rho : G &\rightarrow GL(F^n) \\ g &\rightarrow \rho_g\end{aligned}$$

via $\rho_g(v) = R_g v$ where R_g is the matrix of g .

Example. (2.6)

Given any group G , take $V = F$ the 1-dimensional space, and

$$\begin{aligned}\rho : G &\rightarrow GL(F) \\ g &\rightarrow (id : F \rightarrow F)\end{aligned}$$

is known as the trivial representation of G . So $\deg \rho = 1$ ($\dim_F F = 1$).

Example. (2.7)

Let $G = C_4 = \langle x : x^4 = 1 \rangle$. Let $n = 2$, and $F = \mathbb{C}$. Note that any $R : x \rightarrow X$ will determine $x^j \rightarrow X^j$ as it is a homomorphism, and also we need $X^4 = I$. So we can take X to be diagonal matrix – any such with diagonal entries a root to $x^4 = 1$, i.e. $\{\pm 1, \pm i\}$, or if X is not diagonal then it will be similar to a diagonal matrix by (1.4) ($X^4 = I$).

2.2 Equivalent representations

Definition. (2.8)

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

$$\phi \rho(g) = \rho'(g) \phi \forall g \in G(*)$$

We can understand this more by the following diagram:

$$\begin{array}{ccc} V & \xrightarrow{\rho_g} & V \\ \phi \downarrow & \searrow & \downarrow \phi \\ V' & \xrightarrow{\rho'_{g'}} & V' \end{array}$$

We say ϕ *intertwines* ρ, ρ' . Write $\text{Hom}_G(V, V')$ for the F -space of all these. ϕ is a G -isomorphism if it is also bijective; if such ϕ exists, ρ, ρ' are isomorphic/equivalent representations. If ϕ is a G -isomorphism, we can write (*) as $\rho' = \phi\rho\phi^{-1}$.

Lemma. (2.9)

The relation "being isomorphic" is an equivalent relation on the set of all representations of G (over F).

Remark. (2.10)

If ρ, ρ' are isomorphic representations, they have the same dimension.

The converse may be false: C_4 has four non-isomorphic 1-dimensional representations: if $\omega = e^{2\pi i/4}$ then they are $\rho_j(x^i) = \omega^{ij}$ ($0 \leq i \leq 3$).

Remark. (2.11)

Given G, V over F of dimension n and $\rho : G \rightarrow GL(V)$. Fix basis B for V : we get a linear isomorphism

$$\begin{aligned} \phi : V &\rightarrow F^n \\ v &\rightarrow [v]_B \end{aligned}$$

and we get a representation $\rho' : G \rightarrow GL(F^n)$ isomorphic to ρ :

$$\begin{array}{ccc} V & \xrightarrow{\rho} & V \\ \downarrow \phi & & \downarrow \phi \\ F^n & \xrightarrow{\rho'} & F^n \end{array}$$

(2.12) In terms of matrix representations, we have

$$\begin{aligned} R : G &\rightarrow GL_n(F), \\ R' : G &\rightarrow GL_n(F) \end{aligned}$$

are (G) -isomorphic or equivalent if there exists a nonsingular matrix $X \in GL_n(F)$ with $R'(g) = XR(g)X^{-1} \forall g \in G$.

In terms of linear G -actions, the actions of G on V, V' are G -isomorphic if there exists isomorphisms $\phi : V \rightarrow V'$ such that $g : \phi(v) = \phi(gv) \forall v \in V, g \in G$.

2.3 Subrepresentations

Definition. (2.13)

Let $\rho : G \rightarrow GL(V)$ be a representation of G . We say $W \leq V$ is a G -subspace if it's a subspace and it is $\rho(G)$ -invariant, i.e. $\rho_g(W) \leq W \forall g \in G$. Obviously $\{0\}$ and V are G -subspaces, however.

ρ is *irreducible/simple* representation if there are no proper G -subspaces.

Example. (2.14)

Any 1-dimensional representation of G is irreducible, but not conversely, e.g. D_8 has 2-dimensional \mathbb{C} -irreducible representation.

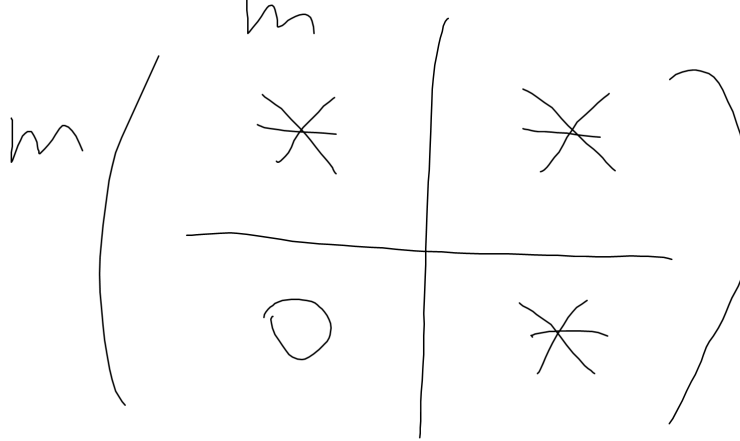
(2.15) In definition (2.13), if W is a G -subspace, then the corresponding map

$$\begin{aligned} G &\rightarrow GL(W) \\ g &\rightarrow \rho(g)|_W \end{aligned}$$

is a representation of G , a *subrepresentation* of ρ .

Lemma. (2.16)

In definition (2.13), given $\rho : G \rightarrow GL(V)$, if W is a G -subspace of V and if $B = \{v_1, \dots, v_n\}$ is a basis containing basis $B_1 = \{v_1, \dots, v_m\}$ of W ($0 < m < n$) then the matrix of $\rho(g)$ w.r.t. B has block upper triangular form as the graph below, for



each $g \in G$.

Example. (2.17)

(i) The irreducible representations of $C_4 = \langle x : x^4 = 1 \rangle$ are all 1-dimensional and four of these are $x \rightarrow i, x \rightarrow -1, x \rightarrow -i, x \rightarrow 1$. In general, $C_m = \langle x : x^m = 1 \rangle$ has precisely m irreducible complex representations, all of dimension 1. In fact, all complex irreducible representations of a finite abelian group are 1-dimensional (use (1.4)* or see (4.4) below).

(ii) $G = D_6$: any irreducible C -representation has dimension ≤ 2 .

Let $\rho : G \rightarrow GL(V)$ be irreducible G -representation. Let r, s be rotation and reflection in D_6 respectively. Let V be eigenvector of $\rho(r)$. So $\rho(r)v = \lambda v$

for some $\lambda \neq 0$. Let $W = \text{span}\{v, \rho(s)v\} \leq V$. Since $\rho(s)\rho(s)v = v$ and $\rho(r)\rho(s)v = \rho(s)\rho(r)^{-1}v = \lambda^{-1}\rho(s)v$, both of which are in W ; so W is G -invariant, i.e. a G -subspace. Since V is irreducible, $W = V$.

Definition. (2.18)

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

Lemma. (2.19)

Suppose $\rho : G \rightarrow GL(V)$ is decomposable with G -invariant decomposition $V = U \oplus W$. If B is a basis $\{\underbrace{u_1, \dots, u_k}_{B_1}, \underbrace{w_1, \dots, w_l}_{B_2}\}$ of V consisting of basis of U and basis of W , then w.r.t. B , $\rho(g)_B$ is a block diagonal matrix $\forall g \in G$ as

$$\rho(g)_B = \begin{pmatrix} [\rho_U(g)]_{B_1} & 0 \\ 0 & [\rho_W(g)]_{B_2} \end{pmatrix}$$

Definition. (2.20)

If $\rho : G \rightarrow GL(V)$, $\rho' : G \rightarrow GL(V')$, the *direct sum* of ρ, ρ' is

$$\rho \oplus \rho' : G \rightarrow GL(V \oplus V')$$

where $\rho \oplus \rho'(g)(v_1 + v_2) = \rho(g)v_1 + \rho'(g)v_2$, a *block diagonal action*. For matrix representations $R : G \rightarrow GL_n(F)$, $R' : G \rightarrow GL_{n'}(F)$, define $R \oplus R' : G \rightarrow GL_{n+n'}(F)$:

$$g \rightarrow \begin{pmatrix} R(g) & 0 \\ 0 & R'(g) \end{pmatrix}$$

3 Complete reducibility and Maschke's theorem

Definition. (3.1)

A representation $\rho : G \rightarrow GL(V)$ is *completely reducible*, or *semisimple*, if it is a direct sum of irreducible representations. Evidently, irreducible implies completely reducible (lol).

Remark. (3.2)

- (1) The converse is false;
- (2) See sheet 1 Q3: \mathbb{C} -representation of \mathbb{Z} is not completely reducible and also representation of C_p over \mathbb{F}_p is not c.r..

From now on, take G finite and $\text{char } F = 0$.

Theorem. (3.3)

Every f.d. representation V of a finite group over a field of char 0 is completely reducible, i.e.

$$V \cong V_1 \oplus \dots \oplus V_r$$

is a direct sum of representations, each V_i irreducible.

It is enough to prove:

Theorem. (3.4 Maschke's theorem, 1899)

Let G be finite, $\rho : G \rightarrow GL(V)$ a f.d. representation, $\text{char } F = 0$. If W is a G -subspace of V , then there exists a G -subspace U of V s.t. $V = W \oplus U$, a direct sum of G -subspaces.

Proof. (1)

Let W' be any *vector subspace* complement of W in V , i.e. $V = W \oplus W'$ as vector spaces, and $W \cap W' = 0$. Let $q : V \rightarrow W$ be the projection of V onto W along W' ($\ker q = W'$), i.e. if $v = w + w'$ then $q(v) = w$. Define

$$\bar{q} : v \rightarrow \frac{1}{|G|} \sum_{g \in G} gq(g^{-1}v)$$

the 'average' of q over G . Note that in order for $\frac{1}{|G|}$ to exist, we need $\text{char } F = 0$.

It still works if $\text{char } F \nmid |G|$.

Claim (1): $\bar{q} : V \rightarrow W$: For $v \in V$, $g(q(g^{-1}v)) \in W$ and $gW \leq W$;

Claim (2): $\bar{q}(w) = w$ for $w \in W$:

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

So these two claims imply that \bar{q} projects V onto W .

Claim (3) If $h \in G$ then $h\bar{q}(v) = \bar{q}(hv)$ ($v \in V$):

$$\begin{aligned}
 h\bar{q}(v) &= h \frac{1}{|G|} \sum_g g \cdot q(g^{-1}v) \\
 &= \frac{1}{|G|} \sum_g h g q(g^{-1}v) \\
 &= \frac{1}{|G|} \sum_g (hg) q((hg)^{-1}hv) \\
 &= \frac{1}{|G|} \sum_g g q(g^{-1}(hv)) \\
 &= \bar{q}(hv) \\
 &= \bar{q}(hv)
 \end{aligned}$$

We'll then show that the kernel of this map is G -invariant, so this gives a G -summand on Thursday.

Let's now show $\ker \bar{q}$ is G -invariant. If $v \in \ker \bar{q}$, then $h\bar{q}(v) = 0 = \bar{q}(hv)$, so $hv \in \ker \bar{q}$. Thus $V = \text{im } \bar{q} \oplus \ker \bar{q} = W \oplus \ker \bar{q}$ is a G -subspace decomposition.

We can deduce (3.3) from (3.4) by induction on $\dim V$. If $\dim V = 0$ or V is irreducible, then result is clear. Otherwise, V has non-trivial G -invariant subspace, W . Then by (3.4), there exists G -invariant complement U s.t. $V = U \oplus W$ as representations of G . But $\dim U, \dim W < \dim V$. So by induction they can be broken up into direct sum of irreducible subrepresentations. \square

The second proof uses inner products, hence we need to take $F = \mathbb{C}$ and can be generalised to compact groups in section 15.

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

- (a) $\langle w, v \rangle = \overline{\langle v, w \rangle} \ \forall v, w$ (Hermitian);
- (b) linear in RHS (sesquilinear);
- (c) $\langle v, v \rangle > 0$ iff $v \neq 0$ (positive definite).

Additionally, \langle, \rangle is *G -invariant* if

- (d) $\langle gv, gw \rangle = \langle v, w \rangle \ \forall v, w \in V, g \in G$.

Note if W is G -invariant subspace of V , with G -invariant inner product, then W^\perp is also G -invariant, and $V \oplus W^\perp$. For all $v \in W^\perp, g \in G$, we have to show that $gv \in W^\perp$. But $v \in W^\perp \iff \langle v, w \rangle = 0 \ \forall w \in W$. Thus by (d), $\langle gv, gw \rangle = 0 \ \forall g \in G \ \forall w \in W$. Hence $\langle gv, w' \rangle = 0 \ \forall w' \in W$. Since we can choose $w = g^{-1}w' \in W$ by G -invariance of W . Thus $gv \in W^\perp$ since g was arbitrary.

Hence if there is a G -invariant inner product on any G -space, we get another proof of Maschke's theorem:

(3.4*) (Weyl's unitary trick)

Let ρ be a complex representation of the finite group G on the \mathbb{C} -space V . Then there is a G -invariant Hermitian inner product on V .

Remark. Recall the *unitary group* $U(V)$ on V : $\{f \in GL(V) : (fu, fv) = (u, v) \ \forall u, v \in V\} = \{A \in GL_n(\mathbb{C}) : A\bar{A}^T = I\} (= U(n))$ by choosing orthonormal

basis.

Sheet 1 Q.12: any finite subgroup of $GL_n(\mathbb{C})$ is conjugate to a subgroup of $U(n)$.

Proof. (2)

There exist an inner product on V : take basis e_1, \dots, e_n and define $(e_i, e_j) = \delta_{ij}$, extended sesquilinearly. Now

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

we claim that \langle, \rangle is sesquilinear, positive definite and G -invariant: if $h \in G$, then

$$\begin{aligned} \langle hv, hw \rangle &= \frac{1}{|G|} \sum_{g \in G} ((gh)v, (gh)w) \\ &= \frac{1}{|G|} \sum_{g' \in G} (g'v, g'w) \\ &= \langle v, w \rangle \end{aligned}$$

for all $v, w \in V$. □

Definition. (3.5, the regular representation)

Recall *group algebra* of G is F -space $FG = \text{span}\{e_g : g \in G\}$. There is a linear G -action

$$h \in G, h \sum_{g \in G} a_g e_g = \sum_{g \in G} a_g e_{hg} (= \sum_{g' \in G} a_{h^{-1}g'} e_{g'})$$

ρ_{reg} is the corresponding representation, the *regular representation* of G . This is faithful of $\dim |G|$. FG is the *regular module*.

Proposition. Let ρ be an irreducible representation of G over a field of characteristic 0. Then ρ is isomorphic to a subrepresentation of ρ_{reg} .

Proof. Take $\rho : G \rightarrow GL(V)$ irreducible and let $0 \neq v \in V$. Let $\theta : FG \rightarrow V$ by $\sum a_g e_g \rightarrow \sum a_g gv$. Check this is a G -homomorphism. Now V is irreducible so $\text{im } \theta = V$ (since $\text{im } \theta$ is a G -subspace).

Also $\ker \theta$ is G -subspace of FG . Let W be G -complement of $\ker \theta$ in FG (Maschke), so that $W < FG$ is G -subspace and $FG = \ker \theta \oplus W$. Thus $W \cong FG / \ker \theta \cong (G\text{-isomorphism}) \text{im } \theta \cong V$. □

More generally,

Definition. (3.7)

Let F be a field. Let G act on set X . Let $FX = \text{span}\{e_x : x \in X\}$ with G -action

$$g(\sum a_x e_x) = \sum a_x e_{gx}$$

The representation $G \rightarrow GL(V)$ where $V = FX$ is the corresponding *permutation representation*. See section 7.

4 Schur's lemma

It's really unfair that such an important result is only remembered by a lemma, so we shall call it a theorem.

Theorem. (4.1, Schur)

- (a) Assume V, W are irreducible G -spaces over field F . Then any G -homomorphism $\theta : V \rightarrow W$ is either 0 or is an isomorphism.
- (b) Assume F is algebraically closed, and let V be an irreducible G -space. Then any G -endomorphism $V \rightarrow V$ is a scalar multiple of the identity map ι_V .