

TOPICS IN MATHEMATICAL SCIENCE VII

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INTRODUCTION TO GROUP REPRESENTATIONS

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Convention

Throughout the course, the symbols $K, \mathbb{k}, \mathbb{F}$ will always be a field. Unless otherwise stated, we assume (for simplicity) that

- all groups are finite;
- all vector spaces are finite-dimensional.

We compose maps from right to left.

We usually denote the identity element of a group G by 1 or 1_G or id_G .

1 Group action

Definition 1.1. Let G be a group and X a set. We say that G acts on X , or X is a G -set, if there is a map $*$: $G \times X \rightarrow X$, with $gx := g * x := *(g, x)$ for all $g \in G$ and $x \in X$, such that

$$1x = x, \quad \text{and} \quad g(hx) = (gh)x.$$

Thinking about this a little bit more, one can see that the action of G on X simply just permutes the elements of X – i.e. G is just some (sub)group of symmetries on X .

When $X = V$ is a vector-space, if we ask for G to only acts by permuting elements, then it could very well destroy the linearity – the best thing about linear algebra – and we lose all the toolkit from linear algebra. The remedy is to “linearise” the definition of action.

Definition 1.2. For a vector space V , we say that G acts linearly on V if G acts on V and

$$g(\lambda u + \mu v) = \lambda g(u) + \mu g(v)$$

for all $g \in G$, all $\lambda, \mu \in K$, and all $u, v \in V$.

Often in practice we just write

$$G \curvearrowright V$$

to denote the existence of linear G -action on V .

2 Linear representations

A linear g -action on V is just a linear transformation for any $g \in G$. So we can repackage the notion of linear G -action using the following.

Recall that the **general linear group** of a vector space V over K is the group of all invertible (K -)linear transformation from V to itself.

$$\mathrm{GL}(V) := \{\phi : V \rightarrow V \mid \phi \text{ invertible linear transformation}\}.$$

The group multiplication is just composition of linear transformations, and the identity element is just the identity map $\mathrm{id} : V \rightarrow V$.

More generally, one can consider $\mathrm{GL}(V)$ for some free R -module V of finite rank for some nice ring R – by nice, usually this would be at least an integral domain. We may look at some examples in the case when $R = \mathbb{Z}$ when we focus on symmetric group representations.

Now we can reformulate the notion of linear G -action as follows.

Definition 2.1. Let G be any (not necessarily finite) group. A finite-dimensional (resp. n -dimensional) K -linear **representation** of G is a group homomorphism

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

for some finite-dimensional (resp. n -dimensional) K -vector space V . The linear transformation ρ_g here is called the **action** of g on V .

Usually, when the underlying field (or ring) is understood, we will drop the adjective ‘ K -linear’ for representations.

Exercise 2.2. Check that representation defines a linear G -action in the sense of Definition 1.2.

While we assumed V is a vector space over a field K here, one can also consider more general setting of “ R -linear representation” when V is an R -lattice (=free R -module of finite rank).

Example 2.3. (1) The **trivial representation** of G is the 1-dimensional representation

$$\mathrm{triv}_G : G \rightarrow \mathrm{GL}(K), \quad g \mapsto \mathrm{id}.$$

(2) $G = \mathfrak{S}_n$ the symmetric group of rank n . The **sign representation** of \mathfrak{S}_n is the 1-dimensional representation

$$\mathrm{sgn} : G \rightarrow \mathrm{GL}(K), \quad \sigma \mapsto \mathrm{sgn}(\sigma),$$

where $\mathrm{sgn}(\sigma) \in \{\pm 1\}$ is the parity (or sign) of the permutation σ .

(3) Let X be a finite G -set (for any finite group G). Denote by KX the K -vector space with basis given by X . Then

$$\pi_X : G \rightarrow \mathrm{GL}(KX), \quad g \mapsto (x \mapsto gx)_{x \in X}$$

defines K -linear G -representation. Any G -representation of such a form is called a **permutation representation**.

Exercise 2.4. Suppose $\rho : G \rightarrow \mathrm{GL}(V)$ is a representation. Show that $\det \rho$ is also a representation.

Exercise 2.5. Consider the additive group of integers $G = (\mathbb{Z}, +)$. Let V be a fixed finite-dimensional \mathbb{C} -vector space. Show that every linear transformation $\phi \in \mathrm{GL}(V)$ defines a unique (not distinguished under isomorphism) \mathbb{C} -linear G -representation.

Recall that for a ring R with identity 1, under addition the element 1 either has infinite or prime, say p , order. The **characteristic** of R , denoted by $\mathrm{char} R$, is 0 in the former case, or p in the latter.

In Example 2.3 (2), we can see that when $\mathrm{char} K = 2$, then sign representation is the same as trivial representation.

In general, changing characteristic drastically change the kind of representations that can appear.

- *Ordinary representation theory* studies K -linear representations over a field K with $\text{char } K = 0$.
- *Modular representation theory* studies K -linear representations over a field K with $\text{char } K = p > 0$ and $p \nmid \#G$.
- *Integral representation theory* studies \mathcal{O} -linear representations over a (nice – such as discrete valuation ring) integral ring \mathcal{O} (but sometimes including \mathbb{Z}) with $\text{char } \mathcal{O} = 0$.

The case of K -linear representations with positive characteristic that does *not* divide the order of group is sometimes called “representations over good characteristics” but can also be regarded as a ‘trivial’ extension of ordinary representation theory – characteristic 0 and good characteristic cases are somewhat the same.

Most of this course will be about ordinary representation theory. We may touch on some integral and modular representation for the symmetric group later in the course.

3 Matrix representations

When V is n -dimensional K -vector space, then $\text{GL}(V)$ is isomorphic to

$$\text{GL}_n(K) := \{\text{invertible } n \times n\text{-matrices with entries in } K\}.$$

This isomorphism of course depends on a basis we pick for V .

Definition 3.1. An n -dimensional *matrix representation* of a group G is a group homomorphism

$$R : G \rightarrow \text{GL}_n(K), \quad g \mapsto R_g.$$

We say that the matrix R_g *represents* the action of g .

It is clear that given an n -dimensional matrix representation, one obtains an n -dimensional K -linear representation (with $V = K^n$), and vice versa (by choosing a basis for V and passes through $\text{GL}(V) \cong \text{GL}_n(K)$).

Example 3.2. Consider $G = C_3 = \langle x \mid x^3 = 1 \rangle$ the cyclic group of order 3. Let us try to see what matrix representations of G look like in the case when $K = \mathbb{C}$.

Suppose that $R_x \in \text{GL}_n(\mathbb{C})$ is diagonal. Since $R_x^3 = R_{x^3} = R_1 = \text{id}$, the diagonal entries are in $\{\omega^k := \exp(2\pi i k/3) \mid 0 \leq k < 3\}$, and we can write $R_x = \text{diag}(\omega^{k_1}, \dots, \omega^{k_n})$ with any $k_i \in \{0, 1, 2\}$ for all $i = 1, \dots, n$. Note that, in this case, R_x^2 will also be a diagonal matrix $\text{diag}(\omega^{2k_1}, \dots, \omega^{2k_n})$.

On the other hand, if R_x is not a diagonal matrix, since R_x is invertible and we work over \mathbb{C} , we can still find $P \in \text{GL}_n(\mathbb{C})$ so that PR_xP^{-1} is diagonal. In other words, we have a *commutative diagram*

$$\begin{array}{ccc} \mathbb{C}^n & \xrightarrow[\cong]{P} & \mathbb{C}^n \\ \text{diag}(\omega^{ik_1}, \dots, \omega^{ik_n}) \downarrow & & \downarrow R_x^i \\ \mathbb{C}^n & \xrightarrow[\cong]{P} & \mathbb{C}^n, \end{array}$$

i.e. the two paths from top left to bottom right resulting the same map. This amounts to say that, up to a change of basis of \mathbb{C}^n , the non-diagonal case is “essentially the same” as the diagonal one.

4 Homomorphism

In mathematics, the word for “essentially the same” is (usually) isomorphism; for this, we need the weaker notion of homomorphism first.

Definition 4.1. Let $\rho : G \rightarrow \text{GL}(V)$ and $\theta : G \rightarrow \text{GL}(W)$ be two K -linear representations of G . A **homomorphism** from V to W is a K -linear transformation such that the following diagram commutes

$$\begin{array}{ccc} V & \xrightarrow{f} & W \\ \rho_g \downarrow & & \downarrow \theta_g \\ V & \xrightarrow{f} & W \end{array}$$

for all $g \in G$, i.e. $f\rho_g = \theta_g f$ for all $g \in G$.

An **isomorphism** from V to W is a homomorphism that is invertible, i.e. $\exists g$ s.t. $gf = \text{id}_V$ and $fg = \text{id}_W$.

Write $\text{Hom}_{KG}(V, W)$ for the space of all homomorphisms from V to W .

Remark 4.2. Older text also calls a homomorphism (sometimes, only for isomorphism) $f : V \rightarrow W$ an **intertwiner**, or that f **intertwines** ρ, θ ; we will try to avoid using this and stick to homomorphism. Older text may say that V, W are equivalent if there is an isomorphism between them. We will drop this redundant language and just say V and W are isomorphic.

Example 4.3. Let us go back to the case when $G = C_3$ and take $n = 1$. We have three representations $R^{(i)}$ with $i = 1, 2, 3$ so that $R_x^{(i)} = \omega^i$. An isomorphism on \mathbb{C} is just a non-zero scalar multiplication $\lambda \cdot -$. As $\lambda R_x^{(i)} \lambda^{-1} = R_x^{(i)} = \omega^i$, we have $R^{(i)} \not\cong R^{(j)}$ whenever $i \neq j$. In fact, by the same reason, we can see that

$$\text{Hom}_{\mathbb{C}G}(R^{(i)}, R^{(j)}) = \{0\}$$

for distinct i, j .

Exercise 4.4. Verify that (a) $\text{Hom}_{KG}(V, W)$ is a K -vector space, and (b) the composition of homomorphisms is also a homomorphism of representations.

Since $\text{Hom}_{KG}(V, W)$ is a K -vector space, we can just write $\text{Hom}_{\mathbb{C}G}(R^{(i)}, R^{(j)}) = 0$ in the above example, instead of the more bulky set notation $\{0\}$.

Exercise 4.5. Consider $G = C_3$ with generator g acting on $X = \{0, 1, 2\}$ by $gi = i + 1 \pmod{3}$. Recall from Example 3.2 that 3-dimensional representation of C_3 is isomorphic to a (matrix) representation $R^{(k_1, k_2, k_3)} : G \rightarrow \text{GL}_3(\mathbb{C})$ with $R_g^{(k_1, k_2, k_3)} = \text{diag}(\omega^{k_1}, \omega^{k_2}, \omega^{k_3})$. Find (k_1, k_2, k_3) so that $\mathbb{C}X \cong R^{(k_1, k_2, k_3)}$.

Exercise 4.6. Let X, Y be two G -sets. Determine the condition on a map $f : X \rightarrow Y$ so that f induces a homomorphism of permutation representations from π_X to π_Y .

5 Group algebra

Definition 5.1. Let KG be the K -vector space with basis G , i.e. $x \in KG \Leftrightarrow x = \sum_{g \in G} \lambda_g g$ with $\lambda_g \in K$ for all $g \in G$.

Define a map

$$KG \times KG \rightarrow KG, \quad \left(\sum_{g \in G} \lambda_g g, \sum_{h \in G} \mu_h h \right) \mapsto \sum_{g, h \in G} \lambda_g \mu_h (gh).$$

It is routine to check that this defines a ring structure on KG with identity given by that of G . We call this ring the **group algebra** of G over K .

Exercise. (1) Show that there is an injective ring homomorphism $K \rightarrow Z(KG) := \{x \in KG \mid xy = yx \forall y \in KG\}$. In other words, the group algebra KG is a **K -algebra**.

(2) Let R be a commutative ring and A be another (possibly non-commutative) ring. Show that if there is an injective ring homomorphism $R \rightarrow Z(A)$, then any A -module is also an R -module.

Lemma 5.2. $\rho : G \rightarrow \text{GL}(V)$ is a (finite-dimensional) K -linear representation of G if, and only if, V has the structure of a (finite-dimensional) left KG -module.

Proof \Rightarrow : For $x = \sum_g \lambda_g g \in KG, v \in V$. It is routine to check that $x \cdot v := \sum_g \lambda_g \rho_g(v)$ defines a left KG -module structure.

\Leftarrow : From the previous exercise, we checked that there is an injective ring homomorphism $K \hookrightarrow Z(KG)$. Hence, we have

$$(\lambda g)(v) = g(\lambda v)$$

for all $g \in G, \lambda \in K, v \in V$. By the axiom of module, V is an abelian group, and so there $0 \in V$ and also well-defined addition operation. Taking $g = 1$ in the above equation, we get that $\lambda v \in V$ for all $\lambda \in K$. Hence, V is a K -vector space.

Now for $g \in G$, define a map $\rho_g : V \rightarrow V$ given by $v \mapsto gv$. We then have

$$g(\lambda u + \mu v) = (\lambda g)(u) + (\mu g)(v) = \lambda \rho_g(u) + \mu \rho_g(v),$$

and so ρ_g is a linear transformation. Since $g^{-1}(g(v)) = (g^{-1}g)v = 1_G \cdot v = v$, we have $\rho_{g^{-1}}\rho_g = \text{id}$, and so $\rho_g \in \text{GL}(V)$.

Finally, the axiom of module says that $(gh)(v) = g(hv)$, which means that $\rho_{gh} = \rho_g \rho_h$. Thus, $g \mapsto \rho_g$ is a group homomorphism. \square

Remark 5.3. One may find in older textbooks that use terminologies like ‘the KG -module V is *afforded* by ρ ’ in the setting of this lemma. We will just use ρ is the representation associated/corresponding to V , or vice versa, to keep the language simple.

Example 5.4. KG is clearly a KG -module where the (left) action is given by (left) multiplication. Thus, we have a G -representation $\rho : G \rightarrow \text{GL}(KG)$ with $\rho_g(\sum_{h \in G} \lambda_h h) := \sum_{h \in G} \lambda_h gh$. This representation is usually called *regular representation* of G .

Exercise 5.5. Let V be the 1-dimensional subspace of KG spanned by $\sum_{g \in G} g$. Show that V is a KG -module and that $\text{triv}_G \cong V$.

Lemma 5.6. $f : V \rightarrow W$ is a homomorphism of K -linear G -representations if, and only if, it is a homomorphism of left KG -modules. Consequently, $\text{Ker}(f)$, $\text{Im}(f)$, $W/\text{Im}(f)$ are naturally K -linear G -representations.

Proof First part: Exercise.

For the second part, just recall that the kernel, image, and quotient of image of any homomorphism of modules are also modules. \square

Remark. In the language of category theory, Lemma 5.2 and 5.6 together says that the category of finite-dimensional K -linear G -representations (where morphisms are homomorphisms) and the category of finitely generated left KG -modules are isomorphic (note that this is stronger than just equivalence of categories).

Exercise 5.7. Verify the first part of Lemma 5.6.

Exercise 5.8. Fix any $n \geq 2$.

(i) Find a generator v such that $\text{sgn} = Kv$. (Hint: Modify the generator $\sum_{g \in G} g$ of the trivial representation.)

(ii) Show that $\text{Hom}_{K\mathfrak{S}_n}(\text{triv}, \text{sgn}) = 0 = \text{Hom}_{K\mathfrak{S}_n}(\text{sgn}, \text{triv})$ when $\text{char } K \neq 2$; otherwise, $\text{triv} \cong \text{sgn}$.

6 Subrepresentation, indecomposable, irreducible

Definition 6.1. Let $\rho : G \rightarrow \text{GL}(V)$ be a K -linear G -representation. A subspace W of V is *G -invariant* if $\rho_g(W) \subset W$. In this case we call the homomorphism $\theta : G \rightarrow \text{GL}(W)$ given by $\theta_g := \rho_g|_W$ a *subrepresentation* of ρ . It is *non-trivial*, or *proper*, if W is non-zero and $W \neq V$.

We say that ρ is *irreducible* (or that V is *simple*) if it admits no proper subrepresentation.

We will use both the terminologies irreducible and simple for representations and modules since they are ‘the same’ notion.

Exercise 6.2. Let $f : V \rightarrow W$ be a homomorphism of representations from $\rho : G \rightarrow \text{GL}(V)$ to $\phi : G \rightarrow \text{GL}(W)$. Show the following directly without using the language of KG -modules.

- $\text{Ker}(f)$ is a G -invariant subspace of V .
- $\text{Im}(f)$ is a G -invariant subspace of W .

Example 6.3. (1) Any 1-dimensional representation is irreducible.

(2) triv_G is a 1-dimensional irreducible subrepresentation of the regular representation; see Exercise 5.5.

(3) Consider $G = D_6 = \langle a, b \mid b^2 = 1 = a^3, abab = 1 \rangle$ and $K = \mathbb{C}$. Consider a 2-dimensional representation $\rho : G \rightarrow \text{GL}(V)$ so that under the basis $\{u, v\}$ we have its matrix representation form given by

$$a \mapsto \begin{pmatrix} \omega & 0 \\ 0 & \omega^{-1} \end{pmatrix} \quad \text{and} \quad b \mapsto \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}.$$

If there is a non-trivial subrepresentation, then it will be 1-dimensional spanned by $w := \lambda u + \mu v$ for some scalar $\lambda, \mu \in K$. Being G -invariant means that $aw, bw \in Kw$. Writing the action out:

$$\begin{cases} bw = b(\lambda u + \mu v) = \mu u + \lambda v, \\ aw = a(\lambda u + \mu v) = \omega \lambda u + \omega^{-1} \mu v \end{cases}$$

Looking at b -action we have some $c \in K$ so that $c\lambda = \mu$ and $c\mu = \lambda$, which yields $\lambda = \pm\mu$.

Looking at a -action we have $aw = \omega^{-1}w$ which means that $\mu\omega^{-2} = \mu$ and so $\mu = 0$. (If we take $aw = \omega w$ then we get $\lambda = 0$.) Hence, combining with $\lambda = \pm\mu$, we have $\lambda = 0$. Thus, $w = 0$. This shows that there is no non-trivial G -invariant subspace and so R is irreducible.

If $\rho : G \rightarrow \text{GL}(V)$ is a G -representation has a subrepresentation with corresponding module W . Then natural inclusion map $W \hookrightarrow V$ naturally defines an injective homomorphism of KG -module. Hence, we know already from module theory that there is a KG -module structure on the quotient space V/W .

Definition 6.4. If ϕ is a subrepresentation of $\rho = \rho_V$, with corresponding KG -modules $W \subset V$ respectively, then the *quotient representation* is the induced homomorphism $\rho_{V/W} : G \rightarrow \text{GL}(V/W)$, i.e. $\rho_{V/W}(g)(v + W) := \rho_g(v) + W$.

Exercise 6.5. Check that quotient representation is indeed a representation of G directly (without using module theory).

Lemma 6.6 (First isomorphism theorem). Let $f : V \rightarrow W$ be a homomorphism of representations $V = (V, \rho), W = (W, \phi)$. Then the quotient representation $V/\text{Ker}(f)$ is isomorphic to the subrepresentation $\text{Im}(f)$ of W .

Proof Just use first isomorphism theorem for KG -modules. □

Looking back at Example 6.3, one can see that looking at matrix really helps to determine subrepresentations. Formulating this more precisely we have the following simple observation.

Lemma 6.7. *Suppose W is a G -invariant subspace of V for a G -representation $\rho : G \rightarrow \text{GL}(V)$. If $\{w_1, \dots, w_m\}$ is a basis of W , then we can extend it to a basis $\mathcal{B} = \{w_1, \dots, w_m, v_{m+1}, \dots, v_n\}$ of V so that, for every $g \in G$, the matrix form R_g of ρ_g with respect to \mathcal{B} is lower block-triangular matrix*

$$R_g = \begin{pmatrix} * & 0 \\ * & R_g|_W \end{pmatrix}. \quad (6.1)$$

For ordinary vector space, having a subspace U , we can immediately get $V = U \oplus V/U$, i.e. there is a complement W of U in V such that $W \cong V/U$. However, this is not true for G -representations (and KG -modules, and also modules over a ring in general) in general.

Definition 6.8. *A representation $\rho : G \rightarrow \text{GL}(V)$ is **decomposable** if there are non-trivial G -invariant subspaces (=subrepresentations) $U, W \subset V$ such that $V = U \oplus W$ (i.e. $V = U + W$ and $U \cap W = 0$ as vector spaces). In this case, we can write $\rho = \rho|_U \oplus \rho|_W$ and call U, W the **direct summands** of V . If no such pair of G -invariant subspace exists, then we say that ρ is **indecomposable**.*

We can formulate this in terms of matrices like Lemma 6.7.

Lemma 6.9. *$\rho = \rho|_U \oplus \rho|_W$ if and only if there is a basis $\mathcal{B}_V := \{u_1, \dots, u_m, w_1, \dots, w_k\}$ so that $\mathcal{B}_U := \{u_i\}_{1 \leq i \leq m}$ is a basis of U and $\mathcal{B}_W := \{w_i\}_{1 \leq i \leq k}$ is a basis of W , and the upper block-triangular matrix R_g in 6.1 has the top-right corner 0 for all g :*

$$R_g^V = \begin{pmatrix} R_g^U & 0 \\ 0 & R_g^W \end{pmatrix}.$$

Here R_g^X is the matrix form of $\rho|_X$ with respect to the basis \mathcal{B}_X for $X \in \{V, U, W\}$.

The more compact way to say the right-hand side of this lemma is that ‘we can *simultaneously block-diagonalize* ρ_g for all g ’.

Of course, direct sum is not just an operation on subspaces. If we have two representations $\rho : G \rightarrow \text{GL}(V), \phi : G \rightarrow \text{GL}(W)$, then we have a new representation $\rho \oplus \phi : G \rightarrow \text{GL}(V \oplus W)$ given by

$$(\rho \oplus \phi)_g(v + w) := \rho_g(v) + \phi_g(w)$$

for any $v \in V$ and $w \in W$.

Exercise 6.10. *If X, Y are two finite G -sets, then we have a new G -set $Z := X \sqcup Y$ given by the disjoint union. The associated permutation representation π_Z is then the direct sum $\pi_X \oplus \pi_Y$.*

Exercise 6.11. *Suppose that X is a finite G -set with G -orbit decomposition $X = O_1 \sqcup \dots \sqcup O_m$. Then we have $\pi_X = \pi_{O_1} \oplus \dots \oplus \pi_{O_m}$.*

Some natural questions once we have the notion of indecomposable and irreducible.

Question. (1) *Can we classify all irreducibles?*

(2) *Can we classify all indecomposables?*

(3) *How to build indecomposable representations from irreducibles?*

(4) *When does being indecomposable imply irreducible?*

(5) *Is there any criteria to guarantee a representation can be decomposed into a direct sum of irreducibles?*

- (6) Is decomposition of representation into direct sum of indecomposable direct summand unique? That is, for a representation V with decompositions $U_1 \oplus \cdots \oplus U_m$ and $W_1 \oplus \cdots \oplus W_n$ with U_i, W_j 's all indecomposable, do we have $m = n$ and $\sigma \in \mathfrak{S}_n$ such that $U_i \cong W_{\sigma(i)}$?
- (7) If we 'divide' a representation into subquotients of irreducibles, is the resulting multi-set of irreducible contribution 'unique'?

Our plan is to answer Questions (4) first – this is given by the Maschke's theorem. And use it, and other tools, to give answers to other questions in the case of ordinary representation theory. We will not give any account for the case of modular representation theory, but just minor remarks here: Question (1) has an answer similar to that of the ordinary case. Question (2) is almost always impossible (for interested audience, search on 'tame-wild dichotomy of representation-type'). Question (3) can only be studied by looking at the homological algebra of KG , which is beyond the scope of this text. Question (4) and (5) does not have any good answer in general. Question (6) and (7) actually have affirmative answer as they are consequence of classical result in ring and module theory (namely, Krull-Schmidt theorem and Jordan-Hölder theorem); these are also beyond the scope of this text.

Before we move on, let us have a look when the Question (4) fails.

Example 6.12. Take $G = C_2 = \langle g \mid g^2 = 1 \rangle$.

First consider the case when $\text{char } K \neq 2$ (e.g. $K = \mathbb{C}$). Recall that the trivial representation $\text{triv}_G \cong K(1 + g)$ is a subrepresentation of the regular representation KG . On the other hand, $C_2 = \mathfrak{S}_2$ has a 1-dimensional representation $\text{sgn} \cong K(1 - g)$. Clearly $\{1 + g, 1 - g\}$ is a basis of KG . This yields a direct sum decomposition

$$KG = K(1 + g) + K(1 - g) = K(1 + g) \oplus K(1 - g) \cong \text{triv} \oplus \text{sgn}.$$

Consider $G = C_2$ with $\text{char } K = 2$ (e.g. $K = \mathbb{F}_2$). Consider regular representation $C_2 \curvearrowright KC_2$. With respect to the canonical basis $\{1, g\}$, the matrix of g -action is given by $R_g = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$. Suppose we can change the basis via $P = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$ to diagonalise R_g . Then R_g becomes

$$\frac{1}{ad - bc} \begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} d & -b \\ -c & a \end{pmatrix} = \frac{1}{ad - bc} \begin{pmatrix} bd - ac & a^2 - b^2 \\ d^2 - c^2 & ac - bd \end{pmatrix}.$$

Hence, we have $b = \pm a$ and $d = \pm c$. Since we are working over characteristic 2, we just get $b = a$ and $d = c$. But in this case the above matrix becomes 0. Hence, R_g cannot be diagonalised and so it is not a direct sum of two 1-dimensional subrepresentations. In particular, it is a 2-dimensional indecomposable. As mentioned, triv is always a subrepresentation and so we have a 1-dimensional subrepresentation triv of KG . One can check that the quotient representation is isomorphic to triv as well, i.e. in pictorial form, we can write:

$$KG = \begin{matrix} \text{triv} \\ \text{triv} \end{matrix}.$$

Exercise 6.13. Complete the argument in the example above by showing that $KG/\text{triv} \cong \text{triv}$ when $\text{char } K = 2$.

Exercise 6.14. Let $A = K[x]/(x^2)$ for any field K . Check that the left A -module ${}_A A$ is indecomposable, i.e. $A \not\cong X \oplus Y$ for some non-trivial submodules X, Y of A .

7 Maschke's theorem

We introduce the following notion to help talking about the Question (5) above.

Definition 7.1. A representation is *completely reducible*, or *semisimple* if it is a direct sum of irreducible representations.

The main aim of this section is to explain the following foundational result of group representation theory, which is the answer to Question (5).

Theorem 7.2. (Maschke) Suppose that G is finite and $\text{char } K$ is coprime to the order of G . For any KG -module V , every submodule U of V admits a G -invariant complement, i.e. $V = U \oplus V/U$ as KG -module.

Proof Let W_0 be any K -vector space complement of U in V , and $\pi : V \rightarrow V$ be the K -linear projection map that projects onto U (i.e. write $v \in V$ as $u + w$ for $u \in U, w \in W_0$, then $\pi(v) = u$). If π is a homomorphism of KG -modules, then W_0 is a KG -module and we are done by Lemma 5.6 – unfortunately this is not true in general. So our goal is to modify π into an idempotent homomorphism. The clever trick is to consider

$$p : V \rightarrow V, \quad v \mapsto \frac{1}{|G|} \sum_{h \in G} h^{-1} \pi h(v).$$

Let us now show that p is a KG -module homomorphism. Indeed, for any $g \in G$, we have

$$p(gv) = \frac{1}{|G|} \sum_{h \in G} h^{-1} \pi h(gv) = \frac{1}{|G|} \sum_{h \in G} g(g^{-1}h^{-1})\pi(hg)v = g \frac{1}{|G|} \sum_{h \in G} h^{-1} \pi h v = gp(v).$$

The averaging by $|G|$ bit seems very unnecessary so far, but we will see soon that this averaging operation makes p a projection onto U . Indeed, first, $\text{Im}(\pi) = U$ implies that $\text{Im}(p) \subset U$, and so it remains to show that $p(u) = u$ for all $u \in U$. Indeed, we have

$$p(u) = \frac{1}{|G|} \sum_{h \in G} h^{-1} \pi \underbrace{h(u)}_{\in U} = \frac{1}{|G|} \sum_{h \in G} h^{-1} h(u) = \frac{1}{|G|} \sum_{h \in G} u = u.$$

Now that we have $p : V \rightarrow V$ a KG -module projection onto U , we get that $\text{Ker}(p)$ is a KG -submodule of V . Hence, we have by first isomorphism theorem that $V/\text{Ker}(p) \cong \text{Im}(p) = U \subset V$ and so $V = \text{Ker}(p) \oplus U$. \square

Corollary 7.3. Every K -linear representation of G semisimple if, and only if, $\text{char } K \nmid |G|$.

Proof \Leftarrow : Consequence of iteratively applying Maschke's theorem (Theorem 7.2).

\Rightarrow : It is enough to show that KG is not semisimple. Suppose on the contrary that KG is semisimple. Let $a := \sum_g g \in KG$ and $V := Ka \subset KG$. Recall that $\text{triv}_G \cong V$. So KG being semisimple means that we must have $KG \cong V \oplus W$ for some left ideal W of KG .

Consider $w = \sum_h \lambda_h h \in W$. Since W is a left ideal of KG , we have $aw \in W$. On the other hand, we also have

$$aw = \left(\sum_g g \right) \left(\sum_h \lambda_h h \right) = \sum_h \lambda_h \left(\sum_g gh \right) = \sum_h \lambda_h a,$$

which means that $aw \in V$. But $V \cap W = 0$ and so we must have $\sum_h \lambda_h = 0$, which means that

$$W \subset W' := \left\{ \sum_g \mu_g g \in KG \mid \sum_g \mu_g = 0 \right\}.$$

The space W' can be rewritten as the kernel of the map (a.k.a. the augmentation map) given by

$$\epsilon : KG \rightarrow K, \quad \sum_g \mu_g g \mapsto \sum_g \mu_g.$$

Thus, $\dim_K W' = |G| - 1 = \dim_K W$ which means that $W = W'$. However, we can also see that $\epsilon(a) = 0$, and so $V \subset W$, a contradiction. \square

Exercise 7.4. Let G be the subgroup of $\mathrm{GL}_n(\mathbb{C})$ given by

$$\left\{ \begin{pmatrix} 1 & 0 \\ n & 1 \end{pmatrix} \mid n \in \mathbb{Z} \right\}$$

Let V be the 2-dimensional \mathbb{C} -vector space. Then we have a natural \mathbb{C} -linear representation $\rho : G \rightarrow \mathrm{GL}(V)$ given by $g \mapsto gv$ (usual applying matrix on vector). Show that V is indecomposable but not irreducible. In particular, Maschke's theorem fails for infinite group even for $K = \mathbb{C}$.

8 Schur's lemma

Definition 8.1. A *division ring*, or a *skew field*, is a ring whose non-zero elements are invertible.

Remark 8.2. A field is a division ring where multiplication is commutative.

The following easy yet fundamental lemma describes the relation between simple modules.

Lemma 8.3 (Schur's lemma). Suppose S, T are simple KG -modules, then

$$\mathrm{Hom}_{KG}(S, T) = \begin{cases} a \text{ division ring,} & \text{if } S \cong T; \\ 0, & \text{otherwise.} \end{cases}$$

If, moreover, K is algebraically closed, then

$$\dim_K \mathrm{Hom}_{KG}(S, T) = \begin{cases} 1, & \text{if } S \cong T; \\ 0, & \text{otherwise.} \end{cases}$$

Proof We prove the first part by showing that any homomorphism $f : S \rightarrow T$ is either zero or an isomorphism. Indeed, for $f \in \mathrm{Hom}_{KG}(S, T)$, we have submodules $\mathrm{Ker}(f) \subset S$ and $\mathrm{Im}(f) \subset T$. Since S is simple, either $\mathrm{Ker}(f) = 0$ or $\mathrm{Ker}(f) = S$. Similarly, since T is simple, either $\mathrm{Im}(f) = T$ or $\mathrm{Im}(f) = 0$. Thus we have

	$\mathrm{Ker}(f) = 0$	$\mathrm{Ker}(f) = S$
$\mathrm{Im}(f) = T$	f isom.	impossible
$\mathrm{Im}(f) = 0$	impossible	$f = 0$.

Assume now that K is algebraically closed, and that $S = T$. We claim that any non-zero homomorphism $f : S \rightarrow S$ is given by a scalar multiple $\lambda \mathrm{id}_S$ of the identity map. Indeed, K being algebraically closed implies that f has an eigenvalue λ , and so $f - \lambda \mathrm{id}_S$ is a non-invertible linear endomorphism on S . It follows from the first part that $f - \lambda \mathrm{id}_S = 0$, and so $f = \lambda \mathrm{id}_S$.

For the case $S \cong T$, we can fix any pair of isomorphisms $f, g : S \rightarrow T$, and so $g^{-1}f : S \rightarrow S$ is an endomorphism. By the previous paragraph, we have $g^{-1}f = \lambda \mathrm{id}_S$ and so $f = \lambda g$. Thus any homomorphism in $\mathrm{Hom}_{KG}(S, T)$ is a scalar multiple of any other non-zero homomorphism. \square

We will now address Question (6). We start with a preliminary lemma.

Lemma 8.4. For any finite-dimensional KG -modules U, V, W , we have

- (1) $\text{Hom}_{KG}(U \oplus V, W) \cong \text{Hom}_{KG}(U, W) \oplus \text{Hom}_{KG}(V, W).$
(2) $\text{Hom}_{KG}(U, V \oplus W) \cong \text{Hom}_{KG}(U, V) \oplus \text{Hom}_{KG}(U, W).$

Proof Exercise (consider the natural projection map $\pi_X : X \oplus Y \rightarrow X$). □

Notation. For a semisimple KG -module M and a simple KG -module S , denote by $[M : S]$ the *multiplicity* of S as a direct summand, up to isomorphism, of M , i.e. the maximal number m such that $M \cong S^{\oplus m} \oplus M'$.

Proposition 8.5 (Krull-Schmidt property). Suppose that K is algebraically closed and $\text{char } K \nmid |G|$. For a finite-dimensional KG -module M and simple KG -module S , we have

$$[M : S] = \dim_K \text{Hom}_{KG}(M, S) = \dim_K \text{Hom}_{KG}(S, M).$$

In particular, if $M \cong S_1 \oplus \cdots \oplus S_s$ and $M \cong T_1 \oplus \cdots \oplus T_t$ are two decomposition of M into direct sum of simple KG -modules, then we have $s = t$ and a permutation $\sigma \in \mathfrak{S}_t$ so that $S_i \cong T_{\sigma(i)}$ for all $1 \leq i \leq t$.

This is only a (very) special case for the Krull-Schmidt theorem, which says that the Krull-Schmidt property (=unique decomposition into direct sum of indecomposables) holds for any finite-dimensional K -algebras (without assumption on the field K); we provide a group representation theoretic proof of this instead.

Proof By Maschke's theorem, we can write $M = S_1 \oplus \cdots \oplus S_s$ for simple modules S_1, \dots, S_s . Hence, we have

$$\dim_K \text{Hom}_{KG}(M, S) = \sum_{i=1}^s \dim_K \text{Hom}_{KG}(S_i, S) = \#\{i \in [1, s] \mid S_i \cong S\} = [M : S],$$

where the first equality comes from repeatedly applying Lemma 8.4, and the second comes from Schur's lemma. The proof for $\dim_K \text{Hom}_{KG}(S, M)$ is similar. One can then show the final statement using the formula and induction on s . □

9 Representations of finite abelian groups

One application of Schur's lemma is that it allows us to say a very useful fact about irreducible representations of a finite abelian group.

Recall that the *center* of a group G is the subgroup

$$Z(G) := \{z \in G \mid zg = gz \ \forall g \in G\}.$$

Likewise, the center of the group algebra KG is the (commutative) subring

$$Z(KG) := \{z \in KG \mid zx = xz \ \forall x \in KG\}.$$

Note that it is enough to check $zg = gz$ for all $g \in G$ when calculating $Z(KG)$. Also, we have natural inclusion (of sets) $Z(G) \hookrightarrow Z(KG)$.

Exercise 9.1. If $H \trianglelefteq G$ is a normal subgroup of G , then $\sum_{h \in H} h \in Z(KG)$.

Lemma 9.2. Let $\rho : G \rightarrow \text{GL}(V)$ be a G -representation. If V is simple and K is algebraically closed, then for each $z \in Z(KG)$, there is a canonical $\lambda_{V,z} \in K^\times$ such that the assignment $z \mapsto \lambda_{V,z}$ restricts to a group homomorphism $\xi_V : Z(G) \rightarrow K^\times$.

Proof It is routine to check that the map

$$f_z : V \rightarrow V, \quad v \mapsto zv(= \rho_z(v))$$

is K -linear. Since $zg = gz$ for all $g \in G$, we have $f_z \rho_g = \rho_g f_z$ for all $g \in G$. Thus, f_z satisfies the condition of being a KG -homomorphism (note that this is possible without V being simple nor K being algebraically closed).

Suppose now that V is simple and K is algebraically closed. It then follows from Schur's lemma (Lemma 8.3) that $f_z = \lambda_{V,z} \text{id}_V$ for some $\lambda_{V,z} \in K^\times$. It is routine (Exercise) to check that ξ_V is a group homomorphism. (More generally, $Z(KG) \rightarrow K^\times$ is a semigroup homomorphism.) \square

Proposition 9.3. *For K algebraically closed, every irreducible K -linear representation of a finite abelian group is 1-dimensional.*

Proof Let G be a finite abelian group and V a simple KG -module. As in Lemma 9.2, for each $z \in G = Z(G)$, we have $f_z = \lambda_{V,z} \text{id}_V \in \text{End}_{KG}(V) := \text{Hom}_{KG}(V, V)$. Hence, for any non-zero $v \in V$, Kv is a non-zero G -invariant subspace of V , and so irreducibility of V implies that $Kv = V$. \square

Remark 9.4. One can prove this without so much representation theory. Just use the fact that commuting diagonalizable matrices can be simultaneously diagonalized.

Exercise 9.5. *Proposition 9.3 can fail without the algebraically closed assumption. Consider $G = C_3 = \langle g \mid g^3 = 1 \rangle$ and K be a field with $\text{char } K = 0$. Define a matrix G -representation $R : G \rightarrow \text{GL}_2(K)$ given by*

$$R_g := \begin{pmatrix} 0 & 1 \\ -1 & -1 \end{pmatrix},$$

(1) *Show that when $K = \mathbb{R}$, R is an irreducible \mathbb{R} -linear C_3 -representation.*

(2) *For $K = \mathbb{C}$, find $i, j \in \{1, 2, 3\}$ so that $R \cong R^{(i)} \oplus R^{(j)}$ (for the $R^{(a)}$'s given in Example 4.3).*

Recall that every finite abelian group G is isomorphic to the direct product $C_{n_1} \times \cdots \times C_{n_r}$ of cyclic groups. Also, over an algebraically closed field K , the n -th root of 1 forms the cyclic group C_n of order n :

$$C_n \cong \{x \in K^\times \mid x^n = 1_K\} =: \mu_n.$$

Proposition 9.6. *Over an algebraically closed field K with $\text{char } K \nmid |G|$, A finite abelian group $G \cong C_{n_1} \times \cdots \times C_{n_r}$ has exactly $|G|$ irreducible K -linear representations, each of which is labelled by a tuple $(\lambda_1, \dots, \lambda_r) \in \prod_{i=1}^r \mu_{n_i}$.*

Proof A finite abelian group G is of the form $C_{n_1} \times \cdots \times C_{n_r}$. Let g_i be the generator of the factor C_{n_i} . Take an irreducible representation $\rho : G \rightarrow \text{GL}(V)$. It follows from Lemma 9.2 Proposition 9.3 that $\dim_K V = 1$ with each g_i acts by multiplying a scalar $\lambda_{V,i} \in K$. Since $g_i^{n_i} = 1$, we have $\lambda_{V,i}^{n_i} = 1 \in \mu_{n_i}$. Thus, $V \mapsto (\lambda_{V,1}, \dots, \lambda_{V,r})$ defines a map α from the set of (representative of) isomorphism classes of irreducible representations

$$\alpha : \{\text{irreducible representation } V\} / \cong \rightarrow \mu_{n_1} \times \mu_{n_2} \times \cdots \times \mu_{n_r}.$$

α injective: Suppose that $(\lambda_{V,i})_i = (\lambda_{V',i})_i$, then g_i acts the same way for all i , and so $V \cong V'$.

α surjective: Given $(\lambda_i)_i \in \mu_{n_1} \times \cdots \times \mu_{n_r}$. Define a map $\rho : G \rightarrow \text{GL}_1(K) = K^\times$ as follows. Take $\rho(g_i) := \lambda_i$ for all $i = 1, \dots, r$. In general, any $g \in G$ is of the form $g = g_1^{a_1} \cdots g_r^{a_r}$, and we define $\rho(g) := \lambda_1^{a_1} \cdots \lambda_r^{a_r}$. It is clear that ρ is a group homomorphism. \square

Remark 9.7. α fails to be injective when $p := \text{char } K$ divides $|G|$ as $\#\{x \in K \mid x^n = 1\} < n$ when $p \mid n$ (note: $x^p - 1 = (x - 1)^p$ over such a field). Nevertheless, a similar argument can still applies (note: Proposition 9.3 still holds) – for example, there is *only* one irreducible representation over a p -group (i.e. a group where every element has order p^k for some k), namely, the trivial representation.

Example 9.8. For $G = C_3$ and $K = \mathbb{C}$, it follows from Proposition 9.6 that the three (pairwise non-isomorphic) irreducible 1-dimensional $R^{(i)}$ from Example 4.3 are all the irreducible (hence, indecomposable, by Maschke) representations up to isomorphism.

Example 9.9. Recall that the [Klein 4-group](#) V_4 is the abelian group of order 4 given by $\langle a, b \mid a^2 = 1 = b^2, ab = ba \rangle \cong C_2 \times C_2$. Thus we have 4 (isomorphism classes of) irreducible representations $\rho_{(0,0)}, \rho_{(1,0)}, \rho_{(0,1)}, \rho_{(1,1)}$ where

$$\rho_{(i,j)} : \begin{cases} a \mapsto (-1)^i, \\ b \mapsto (-1)^j, \\ ab \mapsto (-1)^{i+j} \end{cases}$$

for all $i, j \in \{1, 2\}$.

Proposition 9.10. Let G be a finite group and K be an algebraically closed field with $\text{char } K \nmid |G|$. If every irreducible K -linear G -representation is 1-dimensional, then G is abelian.

Proof By Maschke's theorem (Theorem 7.2), we have $KG = S_1 \oplus \cdots \oplus S_n$ for simple KG -modules S_1, \dots, S_n . By assumption, we have $\dim_K S_i = 1$ and so we can write $S_i = Kv_i$ with $\mathcal{B} := \{v_i\}_{1 \leq i \leq n}$ forming a K -basis of KG . Thus, with respect to this basis, the matrix of every $g \in G$ of the regular representation is a diagonal matrix and pairwise commute. Note that the regular representation $\rho : G \rightarrow \text{GL}(KG)$ has $\text{Ker}(\rho) = 1$ (the matrix of ρ_g with respect to the canonical basis G is a non-trivial permutation matrix for all element $g \neq 1_G$ of G), and so $\text{Im}(\rho) \cong G$ has pairwise commuting elements, i.e. G is abelian. \square

Finally, we show one small application of representation theory on group theory – how existence of certain type of representations guarantee a finite abelian group is cyclic.

Proposition 9.11. For a finite group G and K algebraically closed, if there is an irreducible representation $\rho : G \rightarrow \text{GL}(V)$ with $\text{Ker}(\rho) = 1_G$ (i.e. ρ is [faithful](#)), then the center $Z(G)$ of G is cyclic.

Proof Consider the group homomorphism $\xi_V : Z(G) \rightarrow K^\times$ of Lemma 9.2. $\xi_V(z) = 1$ implies that z acts trivially on V . Since $\text{Ker}(\rho) = 1_G$, we have $\xi_V(z) = 1$ implies that $z = 1_G$. Hence, ξ_V is injective, which means that $\text{Im}(\xi_V) \cong Z(G)$. Since K^\times is abelian and $Z(G)$ is finite, $\text{Im}(\xi_V) \cong Z(G)$ is isomorphic to product of cyclic groups, say, $C_{p_1^{n_1}} \times \cdots \times C_{p_r^{n_r}}$ with p_i primes.

Claim: p_i 's are pairwise distinct.

Proof of Claim: Consider $m := \text{lcm}(p_1^{n_1}, \dots, p_r^{n_r})$, which has $m \leq p_1^{n_1} \cdots p_r^{n_r}$ always.

For any generator g_i of the factor $C_{p_i^{n_i}}$ (any $1 \leq i \leq r$), we have $(g_i)^{p_i^{n_i}} = 1$, and so $(g_i)^m = 1$. However, $\{x \in K^\times \mid x^m = 1\}$ is a group (under multiplication) of order at most m , and so we have $m = n = p_1^{n_1} \cdots p_r^{n_r}$. \blacksquare

It follows from the claim and the Chinese Remainder theorem that $\text{Im}(\xi_V) \cong C_n$ for $n := p_1^{n_1} \cdots p_r^{n_r}$, and now we are done. \square

10 Irreducible and regular representations

Over a field in good characteristic, we have completely answered Question (1) now for finite abelian groups in the previous section; we will give some partial progress towards Question (1) for other finite groups now. (If you are ring theorists, then this section is just a corollary of the Artin-Wedderburn theorem combined with Maschke's theorem.)

Careful audience may notice from the previous two propositions that “everything” is encoded within the regular representation $V = KG$.

Lemma 10.1 (Yoneda). *Let M be any KG -module. Then we have a K -vector space isomorphism $\text{Hom}_{KG}(KG, M) \cong M$.*

Proof Take any $m \in M$, define a map $f_m : KG \rightarrow M$ that maps $x \mapsto xm$. It is routine to check that this is a homomorphism of KG -modules. Now we have a K -linear map

$$\alpha : M \rightarrow \text{Hom}_{KG}(KG, M), \quad m \mapsto (f_m : x \mapsto xm).$$

α is injective: $f_m = 0$ means that $m = f(1_{KG}) = 0$.

α is surjective: For any $f \in \text{Hom}_{KG}(KG, M)$, f is determined by the image of 1_{KG} under f , since f is a K -linear map, G is a basis of KG , and $g(f(1)) = f(g1) = f(g)$ holds for all $g \in G$. Hence, $f = f_m$ where $m = f(1_{KG})$, and so α is surjective. \square

Remark 10.2. (1) Actually, $\text{Hom}_{KG}(KG, M)$ can be equipped with a KG -module structure as KG is a KG -bimodule (see later section) and the isomorphism is actually a KG -module isomorphism.

(2) For category theorist: we view KG as a category \mathcal{C} with single object $*$ and morphisms $\mathcal{C}(*, *) := KG$. A KG -module M is the same as a functor $F : \mathcal{C} \rightarrow \text{Vec}_K$ valued in the category of K -vector spaces via $F(*) := M$. Homomorphisms between KG -modules are just natural transformations of such functors.

Proposition 10.3. *Suppose that $\text{char } K \nmid |G|$. Then, up to isomorphism, every irreducible G -representation is a quotient representation of the regular representation.*

Proof Let V be a simple KG -module and $v \in V$ a non-zero element. Consider the KG -module homomorphism $f_v : KG \rightarrow V$ that maps $f_v(x) := xv$ as in Lemma 10.1. Then $\text{Im}(f_v) \subset V$ is a quotient of the KG -module KG , and also a KG -submodule of V . As V is simple, and $f_v \neq 0$, we have $\text{Im}(f_v) \cong V$. \square

Remark 10.4. The same result actually holds without the assumption on characteristic and also holds if we replace ‘quotient’ by ‘sub’. Under good characteristic, we can deduce the ‘sub’ version of the lemma as $\text{Im}(f_v)$ is a direct summand of V . For the case when $\text{char } K$ divides $|G|$, we can either use the fact that KG is a so-called ‘symmetric algebra’ (meaning that $(KG)^* \cong KG$, see later section on ‘Dual representation’), which allows us to dualise a surjective homomorphism $KG \twoheadrightarrow V$ to an injective one $V^* \hookrightarrow (KG)^* \cong KG$. Then use the fact that dual representation preserves irreducibility and the fact that dualisation is an involutive operation on the set of (isomorphism classes of) irreducible representations.

Corollary 10.5. *For a finite group G , there are only finitely many irreducible representations up to isomorphism when $\text{char } K \nmid |G|$.*

Proof This is because KG is a finite-dimensional KG -module, so we can only have finitely many quotients of KG . The claim now follows from Proposition 10.3. \square

Corollary 10.6. *Suppose K is algebraically closed with $\text{char } K \nmid |G|$. Let $\{S_1, \dots, S_r\}$ be the complete set of isomorphism classes of simple KG -modules. Then we have KG -module isomorphism*

$$KG \cong S_1^{d_1} \oplus \dots \oplus S_r^{d_r}$$

with $d_i = \dim_K S_i$ for all $1 \leq i \leq r$.

Proof By Maschke’s theorem and Proposition 10.3, we have a (unique, by Krull-Schmidt property Proposition 8.5) decomposition

$$KG \cong S_1^{[KG:S_1]} \oplus \dots \oplus S_r^{[KG:S_r]}$$

of KG into a direct sum of simple modules S_1, \dots, S_r with $[KG : S_i] \geq 1$. In fact, Proposition 8.5 already tells us that $d_i = [KG : S_i] = \dim_K \operatorname{Hom}_{KG}(KG, S_i)$. By Lemma 10.1, we have $[KG : S_i] = \dim_K S_i$, and the assertion follows. \square

Our next goal is to relate the number r with group-theoretic information of G . On the way, we will also show a ring-theoretic description of KG – in ring theoretic terms, what we want to do is to find Artin-Wedderburn decomposition of KG .

Definition 10.7. Let C be a conjugacy class in G . The **class sum** is the element $\bar{C} := \sum_{g \in C} g \in KG$.

Recall that the center $Z(A) := \{a \in A \mid ab = ba \forall b \in A\}$ of a ring A is commutative.

Proposition 10.8. Suppose C_1, \dots, C_r are all conjugacy classes of G . Then $\{\bar{C}_1, \dots, \bar{C}_r\}$ is a K -basis of $Z(KG)$.

Note that Proposition 10.8 requires no characteristic assumption.

Proof (1) $\bar{C}_i \in Z(KG)$ for all i : By definition, $g\bar{C}_i g^{-1} = \bar{C}_i$ for any $g \in G$, so we have $g\bar{C}_i = \bar{C}_i g$ which implies, by linearity, that $\bar{C}_i \in Z(KG)$.

(2) $\{\bar{C}_i\}_i$ is linear independent: Simply because each $g \in G$ lies in precisely one conjugacy class.

(3) Spanning: Suppose that $v = \sum_g \lambda_g g \in Z(KG)$. Then for all $h \in G$ we have

$$v = hvh^{-1} = \sum_g \lambda_g hgh^{-1} = \sum_{k \in G} \lambda_{h^{-1}kh} k.$$

Hence, as G is the basis of KG , comparing coefficients yields $\lambda_g = \lambda_{hgh^{-1}}$ for all $g, h \in G$. In other words, λ_g is constant over the conjugacy class containing g . This means that v is in the span of $\{\bar{C}_i\}_{i=1, \dots, r}$. \square

Lemma 10.9. Let $\operatorname{Mat}_n(K)$ be the ring of $n \times n$ -matrices. Then we have a ring isomorphism $Z(\operatorname{Mat}_n(K)) \cong K$.

Proof There is a map $K \rightarrow Z(\operatorname{Mat}_n(K))$ given by $\lambda \mapsto \lambda \operatorname{id}$; it is routine to check that this is a ring isomorphism (Exercise). \square

Definition 10.10. For rings A, B , we have a new ring $A \times B$ called the **direct product** of A and B given by the usual Cartesian product on the underlying set with multiplication $(a, b)(a', b') := (aa', bb')$.

Exercise 10.11. (i) Show that there is a ring isomorphism $\operatorname{End}_A(A)^{\operatorname{op}} \cong A$ for any ring A , where, for a ring Λ

- $\operatorname{End}_\Lambda(X) := \operatorname{Hom}_\Lambda(X, X)$ is the **endomorphism ring** of Λ -module X with multiplication given by composition of maps, and
- $\Lambda^{\operatorname{op}}$ is the **opposite ring** of a ring Λ with multiplication $a \cdot_{\operatorname{op}} b := b \cdot a$.

(ii) Show that $Z(A \times B) = Z(A) \times Z(B)$.

(iii) Suppose M, N are A -modules with $\operatorname{Hom}_A(M, N) = 0 = \operatorname{Hom}_A(N, M)$. Show that $\operatorname{End}_A(M \oplus N) = \operatorname{End}_A(M) \times \operatorname{End}_A(N)$.

(iv) Suppose S is a simple KG -module over an algebraically closed field K . Show that there is a ring isomorphism $\operatorname{End}_{KG}(S^{\oplus m})^{\operatorname{op}} \cong \operatorname{Mat}_m(K)$.

Theorem 10.12. Over an algebraically closed field K with $\operatorname{char} K \nmid |G|$, we have a ring isomorphism

$$KG \cong \operatorname{Mat}_{d_1}(K) \times \cdots \times \operatorname{Mat}_{d_r}(K),$$

where $\operatorname{Mat}_n(K)$ is the ring of $n \times n$ -matrices over K , and r is the number of conjugacy classes of G .

Proof We have ring isomorphisms

$$\begin{aligned}
(KG)^{\text{op}} &\cong \text{End}_{KG}(KG) && \text{by Ex 10.11(i)} \\
&\cong \text{End}_{KG}(S_1^{d_1} \oplus \cdots \oplus S_r^{d_r}) && \text{by Cor 10.6} \\
&\cong \text{End}_{KG}(S_1^{d_1}) \times \cdots \times \text{End}_{KG}(S_r^{d_r}) && \text{by Schur's lemma + Ex 10.11(iii)} \\
&\cong \text{Mat}_{d_1}(K) \times \cdots \times \text{Mat}_{d_r}(K) && \text{by Exercise 10.11(iv).}
\end{aligned}$$

Note that $\text{Mat}_d(K)^{\text{op}} \cong \text{Mat}_d(K)$. Hence, we can apply Lemma 10.9 and Exercise 10.11 (ii) to get the following ring isomorphisms

$$Z(KG) \cong Z(\text{Mat}_{d_1}(K) \times \cdots \times \text{Mat}_{d_r}(K)) \cong Z(\text{Mat}_{d_1}(K)) \times \cdots \times Z(\text{Mat}_{d_r}(K)) \cong K \times \cdots \times K.$$

In particular, we have $r = \dim_K Z(KG)$, which is the same as the number of conjugacy classes in G by Proposition 10.8. \square

Remark 10.13. For K algebraically closed with $\text{char } K = p > 0$, the number of isoclasses of simple KG -modules coincides with the p' -conjugacy classes, i.e. conjugacy class C such that p does not divide $|C|$. The proof is much more involved and require closer comparison between $KG/\text{rad } KG$ and $Z(KG)$, where $\text{rad } KG$ is the Jacobson radical of KG .

Exercise 10.14. Recall from Example 6.3 that there is a 2-dimensional irreducible representation V_2 of $G = D_6 = \langle a, b \mid a^3 = 1 = b^2 \rangle$.

- (1) Find $u, v \in KG$ so that the $K\{u, v\}$ is the subrepresentation of KG that is isomorphic to V_2 .
- (2) Find a basis $\{v_1, v_2, \dots, v_6\}$ of KG so that

$$KG \cong K\{v_1\} \oplus K\{v_2\} \oplus K\{v_3, v_4\} \oplus K\{v_5, v_6\}$$

as KG -module. Describe each of these subrepresentations (by their name/action).

11 Dual space

Recall that the (K) -dual space V^* of a K -vector space V is the vector space given by linear 1-form

$$V^* := \text{Hom}_K(V, K) = \{\text{linear map } f : V \rightarrow K\}.$$

Let $\rho : G \rightarrow \text{GL}(V)$ be a K -linear G -representation. For any $g \in G$ and K -linear map $\alpha \in V^* := \text{Hom}_K(V, K)$, consider the following map

$$\rho_g^*(\alpha) : V \rightarrow K, \quad v \mapsto \alpha \circ \rho_{g^{-1}}(v) = \alpha(g^{-1}v).$$

Clearly, $\rho_g^* : V^* \rightarrow V^*$ given by $\alpha \mapsto \rho_g^*(\alpha)$ is a K -linear map.

Lemma 11.1. For a representation $\rho : G \rightarrow \text{GL}(V)$. Then $\rho^* : G \rightarrow \text{GL}(V^*)$ given by $g \mapsto \rho_g^*$ is also a G -representation.

Proof (1) $\rho_g^* \in \text{GL}(V^*)$: We have

$$\rho_{g^{-1}}^* \rho_g^*(\alpha) = \rho_{g^{-1}}^*(\alpha \circ \rho_{g^{-1}}) = (\alpha \circ \rho_{g^{-1}}) \circ \rho_g = \alpha \circ (\rho_{g^{-1}} \circ \rho_g) = \alpha.$$

Note that, in particular, we have $(\rho_g^*)^{-1} = \rho_{g^{-1}}^*$.

(2) ρ^* is a group homomorphism: Clearly $\rho_{1_G}^* = \text{id}_{V^*}$. We check $\rho_{gh^{-1}}^* = \rho_g^* \rho_h^*$. Take $\alpha \in V^*$, then we have

$$\begin{aligned} \rho_{gh^{-1}}^* (\alpha) &= \alpha \circ \rho_{(gh^{-1})^{-1}} = \alpha \circ \rho_{hg^{-1}} \\ &= \alpha \circ (\rho_h \rho_{g^{-1}}) = (\alpha \circ \rho_h) \circ \rho_{g^{-1}} \\ &= (\rho_h^* (\alpha)) \circ \rho_{g^{-1}} \\ &= \rho_g^* (\rho_h^* (\alpha)) \\ &= (\rho_g^* \circ \rho_h^*) (\alpha) \end{aligned}$$

□

Remark 11.2. Consider any matrix representation $R : G \rightarrow \text{GL}_n(K)$ associated to $\rho : G \rightarrow \text{GL}(V)$ with respect to a basis $\mathcal{B} = \{v_1, \dots, v_n\}$ of V . Let \mathcal{B}^* be the dual basis of V^* , i.e. $\mathcal{B}^* = \{\alpha_1, \dots, \alpha_n\}$ with $\alpha_i(v_j) = \delta_{i,j}$. Then the matrix representation R^* associated to ρ^* with respect to \mathcal{B}^* has action matrix R_g^* given by the transpose $R_{g^{-1}}^t$ of $R_{g^{-1}}$.

Although $V^* \cong V$ for any (finite-dimensional) K -vector space, this generally does not lift to an isomorphism of KG -modules.

Definition 11.3. A KG -module V is *self-dual* if $V^* \cong V$ as KG -modules.

Exercise. Trivial representation and sign representation are both self-dual.

Proposition 11.4. The regular representation is self-dual.

Proof KG has K -linear basis G . The canonical (dual) basis of $(KG)^*$ is given by $\{\alpha_g \mid g \in G\}$ where $\alpha_g(h) := \delta_{g,h}$, i.e. $\alpha_g(g) = 1$ and $\alpha_g(h) = 0$ for all $h \in G \setminus \{g\}$.

Consider the K -linear map $\alpha : KG \rightarrow (KG)^*$ given by linearly extending $g \mapsto \alpha_g$. This is clearly a K -vector space isomorphism. So we only need to show that α is a KG -module homomorphism. For any $g, h, k \in G$, we have

$$(h\alpha(g))(k) = (h \cdot \alpha_g)(k) = \alpha_g(h^{-1}k) = \delta_{g, h^{-1}k} = \delta_{hg, k} = \alpha_{hg}(k) = (\alpha(gh))(k).$$

This shows the claim. □

Remark. In ring theory, this is the same as saying that KG is self-injective. In fact, KG is a symmetric Frobenius algebra, meaning that $(KG)^* \cong KG$ as a KG - KG -bimodule.

In general, finding self-dual representations amounts to finding a ‘ G -invariant bilinear form’.

Proposition 11.5. Suppose $\langle -, - \rangle : U \times V \rightarrow K$ is a *G -invariant non-degenerate bilinear pairing* of KG -modules U, V , i.e. $\langle gu, gv \rangle = \langle u, v \rangle$ for all $g \in G$ and all $u \in U, v \in V$. Then $U \cong V^*$ as KG -module.

Proof Recall that for finite-dimensional K -vector spaces U, V , a non-degenerate bilinear pairing $\langle -, - \rangle : U \otimes V \rightarrow K$ yields an isomorphism $U \cong V^*$ via $u \mapsto \langle u, - \rangle$. One just needs to check that when $\langle -, - \rangle$ is G -invariant, then this K -vector space isomorphism lifts to a KG -module homomorphism. Indeed, if we write $f_u := \langle u, - \rangle$, then we have

$$f_{gu}(v) = \langle gu, v \rangle = \langle gu, g(g^{-1}(v)) \rangle = \langle u, g^{-1}(v) \rangle = f_u(g^{-1}v) = (g \cdot f_u)(v).$$

This shows the claim. □

12 Tensor product

Definition 12.1. Let V, W be finite-dimensional K -vector space with bases, say, \mathcal{B}, \mathcal{C} respectively. Then the **tensor product** $V \otimes_K W$ (or simplifies to $V \otimes W$ if context is clear) is the finite-dimensional K -vector space with basis given by

$$\{v \otimes w \mid v \in \mathcal{B}, w \in \mathcal{C}\}.$$

Suppose $\mathcal{B} = \{v_1, \dots, v_m\}$ and $\mathcal{C} = \{w_1, \dots, w_n\}$. Then for $v = \sum_i \lambda_i v_i$ and $w = \sum_j \lambda_j w_j$, we can use the short-hand

$$v \otimes w := \sum_{i,j} \lambda_i \mu_j (v_i \otimes w_j) \in V \otimes W.$$

Lemma 12.2. Consider $\lambda \in K$, $v, v' \in V$ and $w, w' \in W$. Then we have the following.

- (1) $(\lambda v) \otimes w = \lambda(v \otimes w) = v \otimes (\lambda w)$.
- (2) $(v + v') \otimes w = v \otimes w + v' \otimes w$.
- (3) $v \otimes (w + w') = v \otimes w + v \otimes w'$.

Proof These are simple algebraic rewriting of symbols. For example, taking basis \mathcal{B}, \mathcal{C} as before, the first equality of (1) is just

$$(\lambda v) \otimes w = \lambda \left(\sum_i \lambda_i v_i \right) \otimes \left(\sum_j \mu_j w_j \right) = \sum_{i,j} \lambda \lambda_i \mu_j (v_i \otimes w_j) = \lambda \sum_{i,j} \lambda_i \mu_j (v_i \otimes w_j) = \lambda(v \otimes w).$$

etc. □

Be very careful that there are elements $V \otimes W$ that can **not** be written in the form of $v \otimes w$ for $v \in V$ and $w \in W$. In particular, one common newbie mistake is to regard the following distinct elements as the same:

$$v_1 \otimes w_1 + v_2 \otimes w_2 \neq (v_1 + v_2) \otimes (w_1 + w_2).$$

The right-hand side is really $v_1 \otimes w_1 + v_1 \otimes w_2 + v_2 \otimes w_1 + v_2 \otimes w_2$.

Lemma 12.3. The space $V \otimes_K W$ does not depend on the choice of basis on V and W .

Proof Take any other basis $\{v'_1, \dots, v'_m\}$ of V and $\{w'_1, \dots, w'_n\}$ of W , with change of basis

$$v_i = \sum_k \alpha_{k,i} v'_k \quad \text{and} \quad w_j = \sum_l \beta_{l,j} w'_l.$$

Then

$$v_i \otimes w_j = \sum_{k,l} \alpha_{k,i} \beta_{l,j} v'_k \otimes w'_l.$$

Hence, $\{v'_k \otimes w'_l\}_{k,l}$ spans $V \otimes_K W$, and this spanning set has size the mn ; thus, it is a basis. □

One can define $V \otimes_K W$ in a basis-free way. Notice that if we write $v \otimes w$ as $\langle v, w \rangle$, then the ‘relations’ in Lemma 12.2 says that $\langle -, ? \rangle$ is like a “bilinear form without value”. This can be phrased more precisely as follows.

Lemma 12.4. Given any bilinear form $b := \langle -, ? \rangle : V \times W \rightarrow K$, there is always a unique K -linear map $\theta_b : V \otimes_K W \rightarrow K$ so that the following diagram commutes:

$$\begin{array}{ccc} V \times W & \xrightarrow{\forall b = \langle -, ? \rangle} & K \\ \downarrow & \searrow & \\ V \otimes_K W & \xrightarrow{\exists! \theta_b} & K \end{array}$$

where the vertical map is given by $(v, w) \mapsto v \otimes w$.

Proof Clear from Lemma 12.2 and the definition of $v \otimes w$ that $\theta_b(v \otimes w) := \langle v, w \rangle$ is the desired (K -linear) map. \square

The *universal property of tensor product* says that for any vector space U that satisfies the property:

- for all bilinear form $b : V \times W \rightarrow K$, there exists a map $a : V \times W \rightarrow U$ and a K -linear map $f : U \rightarrow K$ so that $b = fa$,

then $U \cong V \otimes_K W$.