

PMATH 445 COURSE NOTES

REPRESENTATIONS OF FINITE GROUPS

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1 Embeddings and group algebras (09/08/2021)

We begin the course by recalling Cayley's theorem, a famous result from group theory. It states that every finite group G embeds (there exists an injective homomorphism) into a symmetric group S_n . The proof is simple: let G act on itself by left multiplication, and show that this gives an embedding of G into S_n where $n = |G|$. This result is simple, but it allows us to understand finite groups as subgroups of symmetric groups, where one has many tools to use.

In representation theory, one seeks to understand groups in terms of maps into general linear groups $\mathrm{GL}_n(F)$, where F is a field. This is generally more desirable than an embedding into a symmetric group, as we obtain the full power of linear algebra at our disposal. We will consider all homomorphisms (not just injective ones) from groups to general linear groups, and such homomorphisms are called **representations** of our group. First, we show that every finite field embeds into $\mathrm{GL}_n(F)$ for some field F .

PROPOSITION 1.1

Let F be a field. Every finite group embeds into $\mathrm{GL}_n(F)$ for some $n \geq 1$.

PROOF. Let G be a finite group. By Cayley's theorem, we have an embedding $G \hookrightarrow S_n$ where $n = |G|$. Hence, it suffices to show that S_n embeds into $\mathrm{GL}_n(F)$. Define $\varphi : S_n \rightarrow \mathrm{GL}_n(F)$ by $\psi(\sigma) = P_\sigma$, where P_σ denotes the permutation matrix. Notice that for $\sigma_1, \sigma_2 \in S_n$, we have $\varphi(\sigma_1\sigma_2) = P_{\sigma_1\sigma_2} = P_{\sigma_1}P_{\sigma_2} = \varphi(\sigma_1\sigma_2)$, so φ is a group homomorphism. One can also check that if $\varphi(\sigma) = I$, the identity matrix, then σ must be the identity permutation, so φ is injective. \square

It turns out that this result is not true for infinite groups in general.

EXAMPLE 1.2

Let G be the group consisting of bijective maps from \mathbb{Z}^+ to itself such that f fixes all but finitely integers. There does not exist a field F and $n \geq 1$ such that G embeds into $\mathrm{GL}_n(F)$.

PROOF. First, we note the following fact from linear algebra.

FACT 1. If A and B are commuting diagonalizable matrices, then they are simultaneously diagonalizable. That is, there is a common change of basis that makes both matrices diagonalizable. This result also extends to families of commuting diagonalizable matrices.

Now, we denote by (i, j) the bijective mapping from \mathbb{Z}^+ to itself which swaps i and j and fixes all other integers. Consider the permutations $(1, 2)$, $(3, 4)$, $(5, 6)$, and so on. Note that they pairwise commute. Suppose that there exists an injective homomorphism $\varphi : G \rightarrow \mathrm{GL}_n(F)$ for some $n \geq 1$ and a field F . Let $A_1 = \varphi(1, 2)$, $A_2 = \varphi(3, 4)$, and so on. Observe that we have

$$\varphi((i, i+1)^2) = \varphi(\mathrm{id}) = I,$$

which implies that $A_1^2 = A_2^2 = \cdots = I$. We now recall another fact from linear algebra.

FACT 2. If the minimal polynomial of a matrix has distinct roots over the (algebraically closed) field F , then the matrix is diagonalizable.

We see from above that the minimal polynomial of the A_i must divide $x^2 - 1$, since $A_i^2 - I = 0$. As $x^2 - 1$ has distinct roots, it follows from Fact 2 that all the A_i are diagonalizable. Moreover, by Fact 1, we can assume after a change of basis that each A_i is of the form

$$A_i = \begin{pmatrix} \varepsilon_{1,i} & & 0 \\ & \ddots & \\ 0 & & \varepsilon_{n,i} \end{pmatrix}$$

where $\varepsilon_{1,i}, \dots, \varepsilon_{n,i} \in \{\pm 1\}$. Now we have a problem: there are only 2^n such matrices of the above form, and infinitely many positive integers. Thus, there exist positive integers $i < j$ such that $\varphi(A_i) = \varphi(A_j)$, so φ is not injective, and this yields our contradiction.

Note that this argument needs an adjustment for an algebraically closed field of characteristic 2, since $x^2 - 1 = (x - 1)^2$ does not have distinct roots. In such a case, we can proceed in the same way, except we use distinct 3-cycles instead of 2-cycles. \square

We now turn to the notion of a group algebra.

DEFINITION 1.3

The **group algebra** of the group G over the field k is defined by

$$k[G] = \left\{ \sum_{g \in G} \alpha_g \cdot g : \alpha_g \in k, \alpha_g = 0 \text{ for all but finitely many } g \right\}.$$

We note that $k[G]$ is a ring with a natural addition, and multiplication given by

$$\left(\sum_{g \in G} \alpha_g \cdot g \right) \left(\sum_{h \in G} \beta_h \cdot h \right) = \sum_{y \in G} \left(\sum_{(g,h): gh=y} \alpha_g \cdot \beta_h \right) \cdot y.$$

Notice that the inner sum is finite because by definition, there are only finitely many non-zero α_g and β_h .

REMARK 1.4

We call $k[G]$ a group *algebra* because we have a “copy” of k in $k[G]$ given by $\lambda \mapsto \lambda \cdot 1_G$ for elements $\lambda \in k$, with $\lambda \cdot g = g \cdot \lambda$ for all $g \in G$. We see that $k[G]$ is a k -vector space of dimension $|G|$.

EXERCISE 1.5

Show that $\mathbb{C}[S_3] \cong \mathbb{C} \times \mathbb{C} \times M_2(\mathbb{C})$. Fun fact: using the naive approach to multiply matrices takes $O(n^3)$ operations, but applying this fact reduces the time complexity to $O(n^{2.373})$.

We now prove a version of Cayley’s theorem for group algebras.

PROPOSITION 1.6

Let G be a finite group with $n = |G|$. Then G embeds into $\text{GL}_n(k[G])$.

PROOF. Let G act on $k[G]$ by left multiplication. That is, for $g \in G$, define

$$L_g : k[G] \rightarrow k[G] : \sum_{h \in G} \alpha_h \cdot h \mapsto \sum_{h \in G} \alpha_h \cdot (g \cdot h).$$

Observe that for $g_1, g_2 \in G$, we have

$$L_{g_1} \circ L_{g_2}(x) = L_{g_1}(L_{g_2}(x)) = L_{g_1}(g_2 \cdot x) = g_1 \cdot (g_2 \cdot x) = (g_1 \cdot g_2) \cdot x = L_{g_1 g_2}(x).$$

For the second equality, we can think of G as sitting inside $k[G]$ by identifying $g \in G$ with $1 \cdot g \in k[G]$, so we simply have multiplication in the group algebra. Hence, we see that the map $L : G \rightarrow \text{GL}_n(k[G]) : g \mapsto L_g$ is a group homomorphism. Finally, if L_g is the identity matrix, then $g \cdot x = x$ for all $x \in k[G]$. This implies that $g \cdot 1 = 1$ and so $g = 1$, so $\ker L = \{1\}$. Thus, L is injective and is the desired embedding. \square

Later in the course, we will prove the following important theorem. In short, it states that if G is a finite group and k is an algebraically closed field of characteristic zero, then $k[G]$ is isomorphic to a finite direct product of matrix rings over k . The isomorphism and these matrix rings will completely determine the representation of the group G .

THEOREM 1.7

Let G be a finite group and let k be an algebraically closed field of characteristic zero. Then we have

$$k[G] \cong \prod_{i=1}^s M_{n_i}(k),$$

where

- (1) s is the number of conjugacy classes of G ;
- (2) $n_1^2 + n_2^2 + \cdots + n_s^2 = |G|$;
- (3) $|\{i : n_i = 1\}| = |G/G'|$, where G' denotes the commutator subgroup; and
- (4) $n_i \mid |G|$ for all $1 \leq i \leq s$.

As a corollary of this theorem, one can prove Exercise 1.5 by noting that $\mathbb{C}[S_3]$ has three conjugacy classes: $\{(1)\}$, $\{(12), (13), (23)\}$, and $\{(123), (132)\}$.

To finish off the lecture, we give one more interesting linear algebra fact.

FACT. If $q = p^j$ where p is prime and $j \geq 1$, then

$$|\text{GL}_n(\mathbb{F}_q)| = \prod_{i=0}^{n-1} (q^n - q^i).$$

It is not hard to see why. Let A be an invertible $n \times n$ matrix, and note that A must have linearly independent columns. For the first column, say v_1 , we have $q^n - 1$ choices as we can pick any vector except the zero vector. For the second column, we can choose any vector except those in the span of v_1 , which yields $q^n - q$ choices. One can repeat this argument to obtain the result.

2 k -algebras, modules, and Schur's lemma (09/10/2021)

Recall that for a ring R , the **center** of R is the set

$$Z(R) = \{z \in R : zr = rz \text{ for all } r \in R\}.$$

Note that $Z(R)$ is a commutative subring of R . We can also write $[z, r] = 0$ to denote that $zr = rz$.

DEFINITION 2.1

Let k be a field. We say that R is a **k -algebra** if

- (a) R is a ring; and
- (b) there exists a homomorphism $\phi : k \rightarrow Z(R)$ sending 1_k to 1_R (we assume that ϕ is injective).

Notice that if we identify k with $\phi(k) \subseteq R$, we have a “copy” of k in R . This means that R is a k -vector space in addition to being a ring.

DEFINITION 2.2

Let k be a field, and let R and S be k -algebras. A **k -algebra homomorphism** is a ring homomorphism $\psi : R \rightarrow S$ such that $\psi(\lambda) = \lambda$ for all $\lambda \in k$.

We also have the notion of a module. A module over a ring is a generalization of a vector space over a field.

DEFINITION 2.3

A **(left) R -module** M is an abelian group $(M, +)$ equipped with a map

$$\cdot : R \times M \rightarrow M$$

such that for all $r, s \in R$ and $m, n \in M$, we have

- (a) $(r + s) \cdot m = r \cdot m + s \cdot m$;
- (b) $r \cdot (m + n) = r \cdot m + r \cdot n$;
- (c) $(r \cdot s) \cdot m = r \cdot (s \cdot m)$; and
- (d) $1 \cdot m = m$.

EXAMPLE 2.4

Let $R = M_n(\mathbb{C})$ and $M = \mathbb{C}^{n \times 1}$, the set of column vectors of length n . One can check that M is a (left) R -module equipped with the operation of matrix-vector multiplication.

EXAMPLE 2.5

Left ideals are R -modules by left multiplication. In particular, R itself is a left R -module. If L is a left ideal of R (and we write $L \leq_\ell R$), then L is a submodule of R as a left R -module.

REMARK 2.6

If M_1 and M_2 are R -modules, we define the set

$$\mathrm{Hom}_R(M_1, M_2) = \{f : M_1 \rightarrow M_2 \mid f \text{ is } R\text{-linear}\}.$$

That is, we have $f(r \cdot m_1 + m_2) = r \cdot f(m_1) + f(m_2)$ for all $r \in R$ and $m_1, m_2 \in M_1$. In the case that $M_1 = M_2 = M$, we write

$$\mathrm{Hom}_R(M_1, M_2) = \mathrm{End}_R(M),$$

the endomorphisms from M to itself. Note that $\mathrm{End}_R(M)$ is a ring with composition as the multiplication operation, as the set of linear transformations from a vector space to itself forms a ring.

FACT. If R is a k -algebra and M is a left R -module, then M is a k -vector space.

In a sense, this is clear. We know that M already has scalar multiplication by R , and we have a copy of k sitting inside of R , so if we restrict R to k , we obtain scalar multiplication by k .

DEFINITION 2.7

A left R -module M is **simple** if $M \neq (0)$, and (0) and M are the only submodules of M .

EXAMPLE 2.8

Let $R = \mathbb{Z}$ and $M = \mathbb{Z}/p\mathbb{Z}$ for a prime p . Suppose that $N \subseteq M$ is a submodule with $N \neq (0)$. Then there exists $i \in \{1, \dots, p-1\}$ such that the coset $[i]_p$ is in N . But this implies that $[i]_p^{-1} \cdot [i]_p = [1]_p \in N$. It follows that $N = \mathbb{Z}/p\mathbb{Z}$ and hence M is simple.

EXERCISE 2.9

Let $R = M_n(\mathbb{C})$ and $M = \mathbb{C}^{n \times 1}$. Show that M is simple. (Hint: If we are given a non-zero vector, then we can extend it to a basis, and we can always find a linear transformation to send a basis wherever we like.)

DEFINITION 2.10

A left ideal L of R is a **maximal left ideal** if

- (a) $L \subsetneq R$; and
- (b) there does not exist a left ideal L' such that $L \subsetneq L' \subsetneq R$.

EXERCISE 2.11

Let R be a non-zero ring (that is, $0_R \neq 1_R$). If L is a proper left ideal of R , then there exists a maximal left ideal M such that $L \subseteq M$. In particular, taking $L = (0)$ shows that a maximal left ideal always exists.

FACT. If R is a ring and M is a simple left R -module, then M is isomorphic to R/L (as R -modules), where L is a maximal left ideal.

We give a sketch of the proof of this fact. First, pick $m_0 \in M \setminus \{0\}$. Consider R as a left R -module over itself (by left multiplication), and define

$$\begin{aligned}\Phi : R &\rightarrow M \\ r &\mapsto r \cdot m_0.\end{aligned}$$

- (1) Check that Φ is an R -module homomorphism.
- (2) Show that $\ker \Phi = L$ is a left ideal.
- (3) Show that $\operatorname{im} \Phi$ is a non-zero submodule of M , and hence must be equal to M (as M is simple).

By the first isomorphism theorem, it follows that $R/\ker \Phi = R/L$ is isomorphic to $M = \operatorname{im} \Phi$.

Finally, why must L be maximal? Similarly to the correspondence for groups and rings, we also have correspondence for modules. Indeed, for a module M and a submodule $N \trianglelefteq M$, there is a bijection between the submodules of M/N and the submodules of M that contain N .

We have the canonical projection

$$\begin{aligned}\pi : M &\rightarrow M/N \\ m &\mapsto m + N.\end{aligned}$$

For a submodule Q of M/N , notice that

$$\pi^{-1}(Q) = \{m \in M : \pi(m) \in Q\}$$

is a submodule of M which contains N , since

$$N = \pi^{-1}(0) \subseteq \pi^{-1}(Q).$$

Now, there is a correspondence between submodules of M and the left ideals of R containing L . Since M is simple, it has two submodules. Thus, there are two left ideals of R containing L , namely L and R . Therefore, there is no ideal L' such that $L \subsetneq L' \subsetneq R$, so L is maximal.

As a corollary of the above fact, we obtain the following.

COROLLARY 2.12

If R is a finite dimensional k -algebra and M is a simple left R -module, then M is a finite dimensional k -vector space.

PROOF. We showed that there was a surjection $\Phi : R \rightarrow M : r \mapsto r \cdot m_0$ for $m_0 \neq 0$. The fact that Φ is an R -module homomorphism implies that it is k -linear, as there is a copy of k sitting inside of R . Since R is finite dimensional, it follows that M is also finite dimensional. \square

For the remainder of this lecture, we will turn to proving Schur's lemma.

DEFINITION 2.13

A **division ring** Δ is a ring in which every non-zero element $a \in \Delta$ has a multiplicative inverse $b \in \Delta$ (that is, $ab = ba = 1$).

EXAMPLE 2.14

Consider the quaternions

$$\mathbb{H} = \{a + ib + jc + kd : a, b, c, d \in \mathbb{R}\}$$

with properties $i^2 = j^2 = k^2 = 1$, $ij = k$, and $ji = -k$. Check that \mathbb{H} is a division ring, but not a field.

THEOREM 2.15: SCHUR'S LEMMA

Let R be a ring and let M be a simple left R -module. Then $\text{End}_R(M)$ is a division ring.

PROOF. We already know that $\text{End}_R(M)$ is a ring, so we only need to show that every non-zero element has an inverse. Let $0 \neq f \in \text{End}_R(M)$, which is a linear map $f : M \rightarrow M$. Notice that $\ker f$ is a submodule of M . Since M is simple, $\ker f$ is either (0) or M . The latter is impossible as this would mean that $f = 0$, so we have $\ker f = (0)$, so f is injective. Similarly, $\text{im } f$ is a submodule of M and $\text{im } f \neq (0)$ since $f \neq 0$, so $\text{im } f = M$ since M is simple. This shows that f is surjective. Therefore, f has a set theoretic inverse g . We now show that $g \in \text{End}_R(M)$; that is,

$$g(r \cdot m_1 + m_2) = r \cdot g(m_1) + g(m_2)$$

for all $r \in R$ and $m_1, m_2 \in M$. But f is bijective, so this is equivalent to showing that

$$f(g(r \cdot m_1 + m_2)) = f(r \cdot g(m_1) + g(m_2)).$$

This is indeed the case; we have

$$f(g(r \cdot m_1 + m_2)) = r \cdot m_1 + m_2 = r \cdot f \circ g(m_1) + f \circ g(m_2) = f(r \cdot g(m_1) + g(m_2)). \quad \square$$

3 Endomorphism ring, Jacobson density theorem (09/13/2021)

Recall the setting from before: we had a ring R , a simple left R -module M , and $\Delta := \text{End}_R(M)$, which we showed was a division ring.

PROPOSITION 3.1

- (a) If R is a k -algebra for a field k , then $\Delta := \text{End}_R(M)$ is also a k -algebra.
- (b) If k is algebraically closed and R is a finite-dimensional k -algebra, then $\Delta \cong k$.

PROOF.

- (a) For each $\lambda \in k$, define the map

$$\begin{aligned} \Phi_\lambda : M &\rightarrow M, \\ \lambda &\mapsto \lambda \cdot m. \end{aligned}$$

By $\lambda \cdot m$, we mean that we have a copy $k \subseteq Z(R) \subseteq R$, and M is an R -module and hence a k -vector space. Note that

$$\begin{aligned} \Phi_\lambda(r \cdot m_1 + m_2) &= \lambda \cdot (r \cdot m_1 + m_2) \\ &= \lambda \cdot r \cdot m_1 + \lambda \cdot m_2 \\ &= r \cdot \lambda \cdot m_1 + \lambda \cdot m_2 && (\text{since } k \subseteq Z(R)) \\ &= r \cdot \Phi_\lambda(m_1) + \Phi_\lambda(m_2). \end{aligned}$$

Therefore, Φ_λ is R -linear and so $\Phi_\lambda \in \text{End}_R(M)$. However, it is not enough to show that each Φ_λ is in $\Delta = \text{End}_R(M)$. We also require that our map $\lambda \mapsto \Phi_\lambda$ is a map $k \rightarrow Z(\Delta)$; in other words, we also need $\Phi_\lambda \in Z(\Delta)$. Let $\psi \in \Delta$, and observe that

$$\Phi_\lambda \circ \psi(m) = \lambda \cdot \psi(m) = \psi(\lambda \cdot m) = \psi \circ \Phi_\lambda(m),$$

where the second equality is because the R -linearity of ψ implies k -linearity.

- (b) Recall that if R is a finite dimensional k -algebra, then M is a finite dimensional k -vector space (see Corollary 2.12). Suppose that $\dim_k M =: n < \infty$. Then we have

$$\begin{aligned} \Delta = \text{End}_R(M) &\subseteq \text{End}_k(M) && (R\text{-linearity imposes more conditions than } k\text{-linearity}) \\ &\cong \text{End}_k(k^n) && (M \text{ is an } n\text{-dimensional } k\text{-vector space}) \\ &\cong M_n(k) && (k\text{-linear maps } k^n \rightarrow k^n \text{ are the } n \times n \text{ matrices}) \end{aligned}$$

and thus $\dim_k \Delta = m \leq n^2 < \infty$ for some $m \in \mathbb{Z}$.

We now show that $\Delta \cong k$. Indeed, pick $a \in \Delta$. Notice that a commutes with all elements of k since $k \subseteq Z(\Delta)$, where we can identify k with the set $\{\Phi_\lambda : \lambda \in k\}$. Consider

$$k \subseteq k(a) \subseteq \Delta,$$

where $k(a)$ is the field formed from adjoining a to k ; it is a field because Δ is a division ring and hence a is invertible. Thus, $\dim_k k(a) \leq \dim_k \Delta = m < \infty$. Therefore, $\{1, a, a^2, \dots, a^m\}$ is a linearly dependent set over k , so there exist elements $c_0, c_1, \dots, c_m \in k$, not all zero, such that

$$c_0 + c_1 a + \dots + c_m a^m = 0.$$

But k is algebraically closed, so $a \in k$. This implies that $\Delta \subseteq k$, and hence $\Delta \cong k$. \square

EXERCISE 3.2

Let Δ be a division ring and let M be a left Δ -module. Then M has a basis $B \subseteq M$. That is, there do not exist $\delta_1, \dots, \delta_m \in \Delta$ such that

$$\delta_1 b_1 + \dots + \delta_m b_m = 0$$

for distinct $b_1, \dots, b_m \in B$, and for all $m \in M$, we can write

$$m = \sum_{b \in B} \delta_b b$$

where $\delta_b = 0$ for all but finitely many $b \in B$. (Hint: Use Zorn's lemma.)

For this reason, instead of calling it a left Δ -module, we can call it a **left Δ -vector space**.

REMARK 3.3

Let R be a ring, let M be a simple left R -module, and let $\Delta = \text{End}_R(M)$. Then M is a left Δ -vector space.

PROOF. Recall that $\delta \in \Delta$ is an R -linear map from M to itself. We can consider the operation

$$\begin{aligned} \Delta \times M &\rightarrow M, \\ (\delta, m) &\mapsto \delta \cdot m := \delta(m). \end{aligned}$$

It is straightforward to see that

- $(\delta_1 + \delta_2) \cdot m = \delta_1 \cdot m + \delta_2 \cdot m$,
- $\delta \cdot (m_1 + m_2) = \delta \cdot m_1 + \delta \cdot m_2$,
- $\delta \cdot (\delta \cdot m) = (\delta_1 \cdot \delta_2) \cdot m$, and
- $\text{id} \cdot m = m$,

so M is a left Δ -vector space. □

EXAMPLE 3.4

Let $R = M_n(\mathbb{C})$ and recall that $M = \mathbb{C}^{n \times 1}$ is a simple left R -module. We have

$$\Delta = \mathbb{C} = \{\Phi_\lambda : \lambda \in \mathbb{C}\},$$

where each $\Phi_\lambda(m) = \lambda \cdot m$ for each $\lambda \in \mathbb{C}$. One can show that $\Phi(Av) = A \cdot \Phi(v)$ for all $A \in M_n(\mathbb{C})$ and $v \in \mathbb{C}^{n \times 1}$ only when $\Phi = \Phi_\lambda$ for some $\lambda \in \mathbb{C}$.

We now state the Jacobson Density Theorem, which we will prove in the next lecture.

THEOREM 3.5: JACOBSON DENSITY THEOREM

Let R be a ring, let M be a simple left R -module, and let $\Delta = \text{End}_R(M)$. Then we have a ring $\text{End}_\Delta(M)$ and a map

$$\begin{aligned} \Phi : R &\rightarrow \text{End}_\Delta(M) \\ r &\mapsto \Phi_r : M \rightarrow M \\ &\quad m \mapsto r \cdot m. \end{aligned}$$

Moreover, we have the following properties.

- (1) The map Φ is a ring homomorphism and if R is a k -algebra, then Φ is a k -algebra homomorphism.
- (2) The kernel of Φ is the annihilator of M ; that is,

$$\ker \Phi = \{r \in R : r \cdot m = 0 \text{ for all } m \in M\}.$$

- (3) **Density:** If $m_1, \dots, m_n \in M$ are left linearly independent over Δ and $w_1, \dots, w_n \in M$ are arbitrary elements, then there exists $r \in R$ such that

$$\Phi_r(m_i) = w_i$$

for all $1 \leq i \leq n$ (in particular, we can send finite linear combinations wherever we like).

For now, let's see why the maps Φ_r are Δ -linear so that $\Phi_r \in \text{End}_\Delta(M)$ for each $r \in R$. Let $\delta \in \Delta$ and $m_1, m_2 \in M$. Then we have

$$\begin{aligned} \Phi_r(\delta \cdot m_1 + m_2) &= r \cdot (\delta \cdot m_1 + m_2) \\ &= r \cdot (\delta \cdot m_1) + r \cdot m_2 && \text{(multiplication by } R \text{ is linear)} \\ &= r \cdot \delta(m_1) + r \cdot m_2 && \text{(we have } \delta \in \Delta) \\ &= \delta(r \cdot m_1) + r \cdot m_2 && (\delta \text{ is an } R\text{-linear map)} \\ &= \delta \cdot \Phi_r(m_1) + \Phi_r(m_2), \end{aligned}$$

so Φ_r is Δ -linear as desired.

4 Proof of the Jacobson density theorem (09/15/2021)

We now prove the Jacobson Density Theorem, which we stated in the previous lecture. Recall that R is a ring, M is a simple left R -module, and $\Delta = \text{End}_R(M)$. We already showed that $\text{End}_\Delta(M)$ is a ring, and we defined the map

$$\begin{aligned}\Phi : R &\rightarrow \text{End}_\Delta(M) \\ r &\mapsto \Phi_r : M \rightarrow M \\ m &\mapsto r \cdot m.\end{aligned}$$

PROOF OF THE JACOBSON DENSITY THEOREM.

(1) First, observe that for all $r_1, r_2 \in R$ and $m \in M$, we have

$$\begin{aligned}\Phi(r_1 r_2)(m) &= \Phi_{r_1 r_2}(m) \\ &= (r_1 \cdot r_2) \cdot m \\ &= r_1 \cdot (r_2 \cdot m) \\ &= r_1 \cdot \Phi_{r_2}(m) \\ &= \Phi_{r_1} \circ \Phi_{r_2}(m) \\ &= \Phi(r_1) \circ \Phi(r_2)(m).\end{aligned}$$

Similarly, one can show that $\Phi(r_1 + r_2) = \Phi(r_1) + \Phi(r_2)$ and $\Phi(1) = \text{id}_M$, so Φ is a ring homomorphism. Moreover, if R is a k -algebra, then we can identify k with the set $\{\Phi_\lambda : \lambda \in k\}$, so we have a copy of k in $Z(\Delta)$.

(2) Notice that

$$\begin{aligned}r \in \ker \Phi &\iff \Phi_r : M \rightarrow M \text{ is the zero map} \\ &\iff \Phi_r(m) = 0 \text{ for all } m \in M \\ &\iff r \cdot m = 0 \text{ for all } m \in M,\end{aligned}$$

where the last equivalence follows since we defined Φ_r to be left multiplication by r .

(3) We will proceed by induction on n . For $n = 1$, linear independence just means that $m_1 \neq 0$. For arbitrary $w_1 \in R$, we need to show that there exists $r \in R$ such that $\Phi_r(m_1) = r \cdot m_1 = w_1$. Let

$$N = \{s \cdot m_1 : s \in R\} \subseteq M,$$

which is an R -submodule of M . Notice that $N \neq (0)$ since $m_1 \neq 0$. Since M is simple, we must have $N = M$. In particular, we see that $w_1 \in N$, so there exists $r \in R$ such that $r \cdot m_1 = w_1$.

Assume the result holds for $1 \leq k \leq n-1$ where $n \geq 2$. Let m_1, \dots, m_n be linearly independent over Δ , and let $w_1, \dots, w_n \in M$ be arbitrary. We wish to find $r \in R$ such that $r \cdot m_i = w_i$ for all $1 \leq i \leq n$.

By the induction hypothesis, there exists $a \in R$ such that

$$a \cdot m_i = w_i$$

for all $1 \leq i \leq n-1$. However, we don't know that $a \cdot m_n = w_n$, so we will set $a \cdot m_n =: w \in M$.

CLAIM. There exists $r \in R$ such that

$$r \cdot m_1 = \dots = r \cdot m_{n-1} = 0$$

and $r \cdot m_n =: w' \neq 0$.

To complete the proof, it is enough to prove this claim. To see why, suppose we know the claim holds. We know from the base case that we can send w' wherever we like; in particular, there exists $b \in R$ such that $b \cdot w' = w_n - w$. Notice that we have

$$(a + b \cdot r) \cdot m_i = \begin{cases} w_i & \text{if } 1 \leq i \leq n-1, \\ w + (w_n - w) & \text{if } i = n. \end{cases}$$

Thus, choosing $a + b \cdot r \in R$ does the trick.

PROOF OF CLAIM. Suppose that no such $r \in R$ exists. In particular, if

$$r \cdot m_1 = \cdots = r \cdot m_{n-1} = 0,$$

then this will force $r \cdot m_n = 0$ as well. For $a_1, \dots, a_{n-1} \in M$, we know by the induction hypothesis that there exists $s \in R$ such that

$$s \cdot m_i = a_i$$

for all $1 \leq i \leq n-1$. We can define the map $\theta : M^{n-1} \rightarrow M$ by

$$\theta(a_1, \dots, a_{n-1}) = s \cdot m_n.$$

Is this well-defined? We know such an s exists, but we aren't guaranteed that it is unique. Suppose that $s_1, s_2 \in R$ are such that

$$a_i = s_1 \cdot m_i = s_2 \cdot m_i$$

for all $1 \leq i \leq n-1$. Then

$$(s_1 - s_2) \cdot m_i = a_i - a_i = 0$$

for all $1 \leq i \leq n-1$, and by our assumption above, we obtain

$$(s_1 - s_2) \cdot m_n = 0.$$

This means that $s_1 \cdot m_n = s_2 \cdot m_n$, so even if the choice of s is not unique, the map θ is well-defined. We now show that θ is R -linear. For $b \in R$, we have

$$\begin{aligned} \theta(b \cdot (a_1, \dots, a_n)) &= \theta(b \cdot (s \cdot m_1, \dots, s \cdot m_{n-1})) \\ &= \theta(b \cdot s \cdot (m_1, \dots, m_{n-1})) \\ &= (b \cdot s) \cdot m_n \\ &= b \cdot (s \cdot m_n) \\ &= b \cdot \theta(s \cdot (m_1, \dots, m_{n-1})) \\ &= b \cdot \theta(a_1, \dots, a_{n-1}). \end{aligned}$$

Addition follows from the module structure, and we leave it as an exercise.

For $1 \leq j \leq n-1$, we define the canonical inclusion maps

$$\begin{aligned} i_j : M &\rightarrow M^{n-1} \\ m &\mapsto (0, \dots, 0, m, 0, \dots, 0), \end{aligned}$$

where m is placed in the j -th coordinate. It is easy to see that the i_j are R -linear. We have

$$M \xrightarrow{i_j} M^{n-1} \xrightarrow{\theta} M$$

where i_j and θ are both R -linear, so we have

$$\delta_j := \theta \circ i_j \in \Delta = \text{End}_R(M).$$

Now, we obtain

$$\begin{aligned}
 \delta_1 \cdot m_1 + \cdots + \delta_{n-1} \cdot m_{n-1} &= \delta_1(m_1) + \cdots + \delta_{n-1}(m_{n-1}) \\
 &= \theta \circ i_1(m_1) + \cdots + \theta \circ i_{n-1}(m_{n-1}) \\
 &= \theta(i_1(m_1) + \cdots + i_{n-1}(m_{n-1})) \\
 &= \theta(m_1, \dots, m_{n-1}) \\
 &= \theta(1 \cdot m_1, \dots, 1 \cdot m_{n-1}) \\
 &= 1 \cdot m_n \\
 &= m_n.
 \end{aligned}$$

This implies that m_1, \dots, m_n are left linearly dependent over Δ , which is a contradiction. Therefore, the claim holds, and the result follows by induction. \square

5 Faithful and simple modules, left Artinian rings (09/17/2021)

Note that if M is finite-dimensional as a Δ -vector space, then the map Φ from the Jacobson Density Theorem is surjective. To see why, take a basis $\{m_1, \dots, m_n\}$ for M as a Δ -vector space. If $f \in \text{End}_\Delta(M)$, there exist elements $w_1, \dots, w_n \in M$ such that $f(m_i) = w_i$ for all $1 \leq i \leq n$. But by the Jacobson Density Theorem, there exists $r \in R$ such that $r \cdot m_i = w_i$ for all $1 \leq i \leq n$. Note that a linear transformation is completely determined by where the basis is sent, so $f = \Phi_r$.

Recall that by (2) in the Jacobson Density Theorem, we have

$$\ker \Phi = \text{Ann}_R(M) := \{r \in R : r \cdot m = 0 \text{ for all } m \in M\}.$$

DEFINITION 5.1

A left R -module M is called **faithful** if $\text{Ann}_R(M) = (0)$.

From above, we see that M is faithful if and only if Φ is injective.

DEFINITION 5.2

A ring R is said to be **primitive** if it has a faithful simple module.

Putting our above observations together, we obtain the following result.

COROLLARY 5.3

If R has a faithful simple left R -module M such that $\dim_\Delta M < \infty$ where $\Delta = \text{End}_R(M)$, then the map

$$\Phi : R \rightarrow \text{End}_\Delta(M)$$

from the Jacobson Density Theorem is an isomorphism.

PROOF. The assumption $\dim_\Delta(M) < \infty$ gives surjectivity, and since M is faithful, Φ is also injective. \square

COROLLARY 5.4

If k is an algebraically closed field, R is a finite-dimensional k -algebra, and M is a faithful simple left R -module, then $R \cong M_n(k)$ where $n = \dim_k(M)$.

PROOF. By Proposition 3.1, we know that $\Delta = \text{End}_R(M) \cong k$. Moreover, we showed that $\dim_k M = n < \infty$ in Corollary 2.12. Therefore, we see that

$$\begin{aligned} R &\cong \text{End}_\Delta(M) && \text{(by Corollary 5.3)} \\ &\cong \text{End}_k(M) && \text{(since } \Delta \cong k) \\ &\cong \text{End}_k(k^n) && (M \text{ is an } n\text{-dimensional } k\text{-vector space)} \\ &\cong M_n(k) && (k\text{-linear maps } k^n \rightarrow k^n \text{ are the } n \times n \text{ matrices)} \end{aligned}$$

which completes the proof. \square

DEFINITION 5.5

Let R be a ring. We say that R is **left Artinian** if every descending chain of left ideals of R terminates. That is, for a chain of left ideals

$$L_1 \supseteq L_2 \supseteq L_3 \supseteq \cdots$$

of R , there exists $n \geq 1$ such that $L_n = L_m$ for all $m \geq n$.

EXAMPLE 5.6

- (1) We see that \mathbb{Z} is not left Artinian since we can take the chain of ideals

$$2\mathbb{Z} \supsetneq 4\mathbb{Z} \supsetneq 8\mathbb{Z} \supsetneq \cdots.$$

- (2) Intuitively, $M_n(\mathbb{C})$ is left Artinian since it is an n^2 -dimensional \mathbb{C} -vector space, so for a chain of ideals

$$L_1 \supsetneq L_2 \supsetneq L_3 \supsetneq \cdots,$$

the dimension must eventually decrease, so the chain terminates.

- (3) Similarly, $\mathbb{Z}/6000\mathbb{Z}$ is left Artinian as it only has finitely many subsets, so the sizes of the ideals in a descending chain must decrease.

We can generalize our observations from the previous example. We leave the proof as an exercise.

REMARK 5.7

- (1) If R is a finite-dimensional k -algebra, then R is left Artinian.
- (2) If R is a finite ring, then R is left Artinian.

DEFINITION 5.8

Let R be a ring. Let I be a two-sided ideal of R . We say that I is a **nil ideal** if for every $x \in I$, there exists $n = n(x) \geq 1$ such that $x^n = 0$ (that is, every element in I is nilpotent).

EXAMPLE 5.9

- (1) Let R be any ring. Then (0) is a nil ideal.
- (2) Let $R = \mathbb{Z}/2\mathbb{Z}$. Then $I = 6R = \{[0]_R, [6]_R\}$ is a nil ideal since $[0]_R^1 = [0]_R$ and $[6]_R^2 = [36]_R = [0]_R$.
- (3) Let R be the ring of 2×2 upper triangular matrices over \mathbb{C} ; that is,

$$R = \left\{ \begin{pmatrix} a & b \\ 0 & c \end{pmatrix} : a, b, c \in \mathbb{C} \right\} \subseteq M_2(\mathbb{C}).$$

Then one can check that

$$I = \left\{ \begin{pmatrix} 0 & \alpha \\ 0 & 0 \end{pmatrix} : \alpha \in \mathbb{C} \right\}$$

is an ideal of R , and that it is a nil ideal (by squaring).

We now state the Artin-Wedderburn Theorem and give some remarks.

THEOREM 5.10: ARTIN-WEDDERBURN

Let R be a left Artinian ring. If R has no non-zero nil ideals, then there exists $s \geq 1$, division rings D_1, \dots, D_s , and integers $n_1, \dots, n_s \geq 1$ such that

$$R \cong M_{n_1}(D_1) \times \cdots \times M_{n_s}(D_s).$$

REMARK 5.11

- (1) If k is an algebraically closed field and R is a finite-dimensional k -algebra, then

$$R \cong M_{n_1}(k) \times \cdots \times M_{n_s}(k).$$

- (2) By using Exercise 3 on Assignment 1, we see that if R is also finite, then

$$R \cong M_{n_1}(\mathbb{F}_{q_1}) \times \cdots \times M_{n_s}(\mathbb{F}_{q_s}).$$

This can be observed by noting that if R is finite, then the division rings must also be finite.

- (3) If R is also commutative, then

$$R \cong F_1 \times \cdots \times F_s$$

for fields F_1, \dots, F_s . This is because commutativity forces the matrix rings to be 1×1 . Moreover, the division rings must also be commutative, and so they are fields.

We finish the lecture by giving one last definition.

DEFINITION 5.12

Let R be a ring. Then a proper two-sided ideal P is called a **prime ideal** if whenever $a, b \in R$ are such that $aRb = \{arb : r \in R\} \subseteq P$, we either have $a \in P$ or $b \in P$. We say that R is a **prime ring** if (0) is a prime ideal of R .

EXAMPLE 5.13

Observe that $p\mathbb{Z}$ for a prime p is a prime ideal of \mathbb{Z} . Indeed, if $a, b \in \mathbb{Z}$ are such that $a\mathbb{Z}b = ab\mathbb{Z} \subseteq p\mathbb{Z}$, then $p \mid ab$. This occurs if and only if $p \mid a$ or $p \mid b$, or equivalently, $a \in p\mathbb{Z}$ or $b \in p\mathbb{Z}$. In fact, \mathbb{Z} is a prime ring as it has (0) as a prime ideal.

6 Simple rings, characterization of left Artinian rings (09/20/2021)

When R is commutative, notice that R is prime if and only if R is an integral domain. Indeed, observe that

$$\begin{aligned} R \text{ is prime} &\iff aRb = (0) \text{ implies } a = 0 \text{ or } b = 0 \\ &\iff abR = (0) \text{ implies } a = 0 \text{ or } b = 0 \\ &\iff ab \cdot 1 = 0 \text{ implies } a = 0 \text{ or } b = 0 \\ &\iff ab = 0 \text{ implies } a = 0 \text{ or } b = 0 \\ &\iff R \text{ is an integral domain.} \end{aligned}$$

Being prime can be thought of as an extension of being an integral domain in the case where R is not a commutative ring.

DEFINITION 6.1

A ring R is **simple** if (0) and R are its only two-sided ideals.

PROPOSITION 6.2

If R is a simple ring, then R is prime.

PROOF. Let R be simple. Suppose that $aRb = (0)$ with $a \neq 0$ and $b \neq 0$. Since $a \neq 0$, the two-sided ideal

$$RaR := \{u_1av_1 + \cdots + u_sav_s : s \geq 0, u_i, \dots, u_s, v_1, \dots, v_s \in R\}$$

is equal to R by the simplicity of R . In particular, there exists $s \geq 1$ and $u_s, v_1, \dots, v_s \in R$ such that

$$1 = u_1av_1 + \cdots + u_sav_s. \quad (6.1)$$

Similarly, there exists $t \geq 1$ and $y_1, \dots, y_t, z_1, \dots, z_t \in R$ such that

$$1 = y_1bz_1 + \cdots + y_taz_t. \quad (6.2)$$

Multiplying equations (6.1) and (6.2) together gives

$$1 \cdot 1 = (u_1av_1 + \cdots + u_sav_s)(y_1bz_1 + \cdots + y_taz_t) = \sum_{i=1}^s \sum_{j=1}^t u_i(av_iy_jb)z_j = 0,$$

where the last equality is because $aRb = (0)$ and thus $av_iy_jb = 0$ for any $1 \leq i \leq s$ and $1 \leq j \leq t$. \square

PROPOSITION 6.3

Let D be a division ring and let $n \geq 1$. Then $M_n(D)$ is simple and hence prime.

PROOF. Let I be a non-zero ideal of $M_n(D)$. We want to show that $I = M_n(D)$. Since I is non-zero, there exists a matrix

$$x = \begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{pmatrix} \in I$$

with each $a_{ij} \in D$ and $a_{i_0 j_0} \neq 0$ for some $1 \leq i_0, j_0 \leq n$. For all $1 \leq i, j \leq n$, let e_{ij} be the matrix where the (i, j) -th entry is 1 and all other entries are 0. Then we find that

$$e_{ii_0} x e_{j_0 j} = a_{i_0 j_0} e_{ij} \in I.$$

Since D is a division ring, we know that $a_{i_0 j_0}$ has an inverse. It follows that

$$\begin{pmatrix} a_{i_0 j_0}^{-1} & & 0 \\ & \ddots & \\ 0 & & a_{i_0 j_0}^{-1} \end{pmatrix} a_{i_0 j_0} e_{ij} = e_{ij} \in I$$

for all $1 \leq i, j \leq n$. In particular, we obtain

$$e_{11} + \cdots + e_{nn} = 1 \in I,$$

so we conclude that $I = M_n(D)$ and hence $M_n(D)$ is simple. \square

We now prove a nice characterization of left Artinian rings.

PROPOSITION 6.4

Let R be a ring. Then R is left Artinian if and only if whenever S is a non-empty collection of left ideals of R , then S has a minimal element with respect to inclusion.

PROOF. For the forward direction, suppose that R is left Artinian. Let S be a non-empty collection of left ideals of R . Pick $L_1 \in S$. If L_1 is minimal, we are done. Otherwise, we can pick $L_2 \in S$ such that $L_2 \subsetneq L_1$. We can continue this process, and since R is left Artinian, this terminates at some step L_n as we cannot have an infinite strictly descending chain.

For the converse, assume that for every non-empty collection S of left ideals of R , then S has a minimal element with respect to inclusion. Let $L_1 \supseteq L_2 \supseteq \cdots$ be a descending chain of left ideals of R . Let $S = \{L_1, L_2, \dots\}$. By assumption, there exists $n \geq 1$ such that L_n is a minimal element of S . In particular, we have $L_n = L_m$ for all $m \geq n$, so R is left Artinian. \square

The next theorem will be a key step towards proving the Artin-Wedderburn theorem.

THEOREM 6.5

Let R be a prime left Artinian ring. Then $R \cong M_n(D)$ for some $n \geq 1$ and division ring D . (In fact, the converse is also true.)

PROOF. Let $S = \{Ru : u \in R, u \neq 0\}$ be a collection of left ideals of R . Note that S is non-empty since $R \cdot 1 = R \in S$. Then there exists a minimal element in S by Proposition 6.4, say Rb for some $b \in R$. Notice that Rb is a left R -module (since left ideals are left R -modules).

First, we show that $M = Rb$ is simple. If $N \subsetneq M = Rb$ is a proper left ideal with $N \neq (0)$, then there exists $u \neq 0$ in N such that

$$(0) \subsetneq Ru \subsetneq N \subsetneq M.$$

But we assumed that $M = Rb$ was minimal in S , which is a contradiction.

Next, we show that $M = Rb$ is faithful; that is, $\text{Ann}_R(M) = (0)$. Suppose there exists $a \neq 0$ in $\text{Ann}_R(M)$. Then we have $aM = (0)$ and hence $aRb = (0)$. Since R is prime, it must be that $a = 0$ or $b = 0$. But we assumed that $a \neq 0$ and $b \neq 0$, so this is a contradiction.

Now, we show that $\dim_\Delta M < \infty$ where $\Delta = \text{End}_R(M)$. Suppose to the contrary that M were an infinite-dimensional left Δ -vector space. Then there exist elements $m_1, m_2, \dots \in M$ that are Δ -linearly independent. By the Jacobson Density Theorem, for every $n \geq 1$, there exists $r_n \in R$ such that

$$r_n m_1 = r_n m_2 = \dots = r_n m_{n-1} = 0$$

and $r_n m_n \neq 0$. Define the left ideal

$$L_i = \{r \in R : rm_1 = rm_2 = \dots = rm_i = 0\}$$

for all $i \geq 1$. Notice that $L_1 \supseteq L_2 \supseteq \dots$ and $r_n \in L_{n+1} \setminus L_n$, which implies that these are proper containments. But this is an infinite descending chain of left ideals, which contradicts the fact that R is left Artinian.

In the next lecture, we will finish off the proof of this theorem. \square

7 Opposite ring, spectrum of a ring, Nullstellensatz (09/22/2021)

DEFINITION 7.1

Let S be a ring. The **opposite ring** S^{op} of S is defined to be another ring with the same elements and addition as S , but the multiplication $*$: $S^{\text{op}} \times S^{\text{op}} \rightarrow S^{\text{op}}$ is given by

$$s_1 * s_2 := s_2 \cdot s_1,$$

where \cdot denotes the multiplication in S .

REMARK 7.2

- (1) If S is commutative, then S^{op} is the same as S (since $*$ is the same as \cdot).
- (2) If Δ is a division ring, then Δ^{op} is also a division ring. Indeed, let $a \in \Delta^{\text{op}}$ be non-zero. Then there exists $b \in \Delta$ such that $a \cdot b = b \cdot a = 1_\Delta$, so we have $b * a = a * b = 1_{\Delta^{\text{op}}}$. Hence, a is invertible.

EXERCISE 7.3

Let Δ be a division ring. If M is an n -dimensional left Δ -vector space, then $\text{End}_\Delta(M) \cong M_n(\Delta^{\text{op}})$. Note that if $\Delta = k$ for a field k , then this is just saying that $\text{End}_k(M) \cong M_n(k)$, which is a familiar fact.

Hint: Construct the map $\Psi : \text{End}_\Delta(M) \rightarrow M_n(\Delta^{\text{op}})$ as follows: pick a basis $\{m_1, \dots, m_n\}$ as a left Δ -vector space. For $f \in \text{End}_\Delta(M)$, we have

$$f(m_j) = \sum_{i=1}^n a_{ij} m_i$$

where $a_{ij} \in \Delta$ since f is Δ -linear. Define $\Psi(f) := (a_{ij})$, and show that $\Psi(f \circ g) = \Psi(g) \cdot \Psi(f) = \Psi(f) * \Psi(g)$.

Last time, we were proving Theorem 6.5, which stated that if R is a prime left Artinian ring, then $R \cong M_n(D)$ for some $n \geq 1$ and division ring D . We can now finish the proof.

We can set $n := \dim_{\Delta} M$ as we showed that M is a finite-dimensional left Δ -vector space. Then we have

$$R \cong \text{End}_{\Delta}(M) \cong M_n(\Delta^{\text{op}})$$

by Exercise 7.3, and we are done since $D = \Delta^{\text{op}}$ is a division ring. \square

COROLLARY 7.4

Let k be an algebraically closed field, and let R be a prime finite-dimensional k -algebra. Then $R \cong M_n(k)$.

PROOF. Since R is a finite-dimensional k -algebra, it is left Artinian (see Remark 5.7). Moreover, Proposition 3.1 shows that $\Delta = \text{End}_R(M) \cong k$ where M is a simple left R -module, since k is algebraically closed. \square

For the rest of the lecture, we will consider the connection between prime ideals and nil ideals.

DEFINITION 7.5

We define the **spectrum** of a ring R to be the set of all prime ideals of R , denoted $\text{Spec}(R)$.

EXAMPLE 7.6

For $R = \mathbb{Z}$, we have $\text{Spec}(\mathbb{Z}) = \{p\mathbb{Z} : p \text{ prime}\} \cup \{(0)\}$.

EXAMPLE 7.7

For $R = M_n(\Delta)$ for Δ a division ring, we have $\text{Spec}(M_n(\Delta)) = \{(0)\}$ as we showed that $M_n(\Delta)$ is a simple ring in Proposition 6.3.

EXAMPLE 7.8

For $R = \mathbb{C}[x, y]$, we have

$$\text{Spec}(\mathbb{C}[x, y]) = \{(0)\} \cup \{(f) : f \text{ irreducible}\} \cup \{(x - a, y - b) : a, b \in \mathbb{C}\}.$$

Note that (0) is a prime ideal as $\mathbb{C}[x, y]$ is an integral domain. Every maximal ideal of $\mathbb{C}[x, y]$ is of the form $(x - a, y - b)$, and this is due to the Nullstellensatz which we will prove. The other prime ideals are generated by irreducible polynomials f .

THEOREM 7.9: NULLSTELLENSATZ

Let \mathfrak{M} be a maximal ideal of $\mathbb{C}[x_1, \dots, x_n]$. Then there exist $a_1, \dots, a_n \in \mathbb{C}$ such that

$$\mathfrak{M} = (x_1 - a_1, \dots, x_n - a_n).$$

PROOF. Let $F = \mathbb{C}[x_1, \dots, x_n]/\mathfrak{M}$, which is a field because \mathfrak{M} is maximal. Note that $F \supseteq \mathbb{C}$. Moreover, we have $\dim_{\mathbb{C}} F \leq \aleph_0$ since $\mathbb{C}[x_1, \dots, x_n]$ has a basis $\{x_1^{i_1} \cdots x_n^{i_n} : i_1, \dots, i_n \geq 0\} \cong \mathbb{N}^n$, which is countable.

We claim that F is algebraic over \mathbb{C} . That is, if $t \in F$, then F satisfies $p(t) = 0$ for some $p(x) \in \mathbb{C}[x] \setminus \{0\}$. Note that this implies $F = \mathbb{C}$ since \mathbb{C} is algebraically closed.

Let $t \in F \setminus \mathbb{C}$. Consider the set

$$S = \left\{ \frac{1}{t - \lambda} : \lambda \in \mathbb{C} \right\} \subseteq F.$$

Then S is linearly dependent since \mathbb{C} is uncountable while $\dim_{\mathbb{C}} F \leq \aleph_0$. Thus, there exist distinct elements $\lambda_1, \dots, \lambda_n \in \mathbb{C}$ and $c_1, \dots, c_n \in \mathbb{C}$, not all zero, such that

$$\frac{c_1}{t - \lambda_1} + \cdots + \frac{c_n}{t - \lambda_n} = 0.$$

Multiplying by $\prod_{i=1}^n (t - \lambda_i)$ gives

$$\sum_{i=1}^n c_i \prod_{j \neq i} (t - \lambda_j) = p(t) = 0,$$

where $p(x)$ is a polynomial in $\mathbb{C}[x]$. Note that $p(x)$ is non-trivial since

$$p(\lambda_i) = c_i \prod_{j \neq i} (\lambda_i - \lambda_j) \neq 0.$$

This proves the claim, so $\mathbb{C}[x_1, \dots, x_n]/\mathfrak{M} \cong \mathbb{C}$. Hence, there is a homomorphism

$$\phi : \mathbb{C}[x_1, \dots, x_n] \rightarrow \mathbb{C}$$

such that $\ker \phi = \mathfrak{M}$. Letting $a_i = \phi(x_i)$ for all $1 \leq i \leq n$, we have

$$\phi(x_1^{i_1} \cdots x_n^{i_n}) = a_1^{i_1} \cdots a_n^{i_n}$$

as ϕ is a homomorphism. Since the $x_1^{i_1} \cdots x_n^{i_n}$ form a basis for $\mathbb{C}[x_1, \dots, x_n]$, it then follows that ϕ is simply the evaluation at (a_1, \dots, a_n) map. In particular, $\mathfrak{M} = (x_1 - a_1, \dots, x_n - a_n)$ as desired. \square

THEOREM 7.10

Let R be a ring. Then the intersection of all prime ideals

$$\bigcap_{P \in \text{Spec}(R)} P$$

is a nil ideal of R .

PROOF. Let $N = \bigcap_{P \in \text{Spec}(R)} P$. Suppose that there exists some $x \in N$ which is not nilpotent, and let

$$\mathcal{T} = \{1, x, x^2, x^3, \dots\}.$$

Notice that $0 \notin \mathcal{T}$ since x is not nilpotent. Let

$$S = \{I \trianglelefteq R : I \cap \mathcal{T} = \emptyset\}.$$

We have $(0) \in S$, so S is non-empty. We leave it as an exercise to show that S has a maximal element P .

We claim that P is a prime ideal. Suppose otherwise, so that there exists $a, b \notin P$ such that $aRb \subseteq P$. Since $a \notin P$, we have $RaR + P \supsetneq P$, and similarly, $RbR + P \supsetneq P$ as $b \notin P$. As P is maximal in S , this implies

that $RaR + P \notin S$, so there exists $i \geq 1$ such that $x^i \in RaR + P$. Analogously, we have $RbR + P \notin S$, so there exists $j \geq 1$ such that $x^j \in RbR + P$. It follows that

$$x^{i+j} = x^i \cdot x^j \in (RaR + P)(RbR + P) \subseteq R(aRb)R + P \subseteq P.$$

But this is a contradiction since $P \in S$ implies that $P \cap \mathcal{T} = \emptyset$, but we have $x^{i+j} \in P \cap \mathcal{T}$. Thus, P is a prime ideal, proving the claim.

Now, we find that $x \in N \subseteq P$ since P is prime and N is the intersection of all the prime ideals. However, $x \in \mathcal{T}$, which again contradicts the fact that $P \cap \mathcal{T} = \emptyset$. We conclude that every $x \in N$ must be nilpotent, so N is a nil ideal, as required. \square

8 Sun-tzu, the Artin-Wedderburn theorem (09/24/2021)

We almost have all the tools we need to prove the Artin-Wedderburn theorem. First, we make a remark and prove a couple of results that we need.

REMARK 8.1

If R is a left Artinian ring, then so is R/P where P is an ideal of R by correspondence. Moreover, if P is a prime ideal, then R/P is a prime ring. The converse of this holds when R is commutative.

LEMMA 8.2

Let R be a left Artinian ring.

- (1) Every prime ideal of R is a maximal ideal.
- (2) There are only finitely many prime ideals of R .
- (3) Let P_1, \dots, P_s be all the prime ideals of R . Then for all $i = 1, \dots, s$, we have

$$P_i + \bigcap_{j \neq i} P_j = R.$$

PROOF.

- (1) Let P be a prime ideal of R . By Remark 8.1, R/P is a prime left Artinian ring and hence

$$R/P \cong M_n(D)$$

for a division ring D and some $n \geq 1$ by Theorem 6.5. We know that $M_n(D)$ is simple by Proposition 6.3, so its only ideals are (0) and $M_n(D)$. In particular, R/P is also simple. By correspondence, there are only two ideals of R that contain P . We already know that P and R are ideals that contain P , so they are in fact all of them. Thus, P is maximal.

- (2) Suppose towards a contradiction that we have infinitely many distinct prime ideals P_1, P_2, \dots of R . Recall that if I and J are ideals of R , we define

$$IJ = \left\{ \sum_{k=1}^s i_k j_k : s \geq 1, i_k \in I, j_k \in J \right\}.$$

We have a descending chain of ideals

$$P_1 \supseteq P_1 P_2 \supseteq P_1 P_2 P_3 \supseteq \dots$$

and since R is left Artinian, this chain must terminate. Thus, there exists $n \geq 1$ such that

$$P_1 \cdots P_n = P_1 \cdots P_n P_{n+1} \subseteq P_{n+1}.$$

Since $P_1 \neq P_{n+1}$ and P_1 is a maximal ideal by (1), there exists some element $a_1 \in P_1 \setminus P_{n+1}$. Similarly, for all $i = 1, \dots, n$, there exists $a_i \in P_i \setminus P_{n+1}$. Then, we see that

$$(a_1 R)(a_2 R)(a_3 R) \cdots (a_n R) a_n \subseteq P_1 P_2 P_3 \cdots P_n \subseteq P_{n+1},$$

so we have

$$a_1 R a_2 R \cdots a_n R a_n \subseteq P_{n+1}. \quad (8.1)$$

Since neither a_1 nor a_2 are in P_{n+1} , there exists $r_1 \in R$ such that $a_1 r_1 a_2 \notin P_{n+1}$. This is because P_{n+1} is a prime ideal of R , so $a_1, a_2 \notin P_{n+1}$ implies that $a_1 R a_2 \not\subseteq P_{n+1}$. By (8.1), we find that

$$(a_1 R a_2) R a_3 R \cdots a_n R a_n \subseteq P_{n+1}.$$

Now, $a_1 r_1 a_2$ and a_3 are both not in P_{n+1} , so there exists $r_2 \in R$ such that $a_1 r_1 a_2 r_2 a_3 \notin P_{n+1}$ since P_{n+1} is a prime ideal. Continuing in this manner, we have elements $r_1, r_2, \dots, r_{n-1} \in R$ such that

$$a_1 r_1 a_2 r_2 \cdots a_n r_{n-1} a_n \notin P_{n+1},$$

which contradicts (8.1) since

$$a_1 r_1 a_2 r_2 \cdots a_n r_{n-1} a_n \in a_1 R a_2 R \cdots a_n R a_n.$$

We conclude that R must have finitely many prime ideals.

(3) Let P_1, \dots, P_s be the prime ideals of R , and fix $1 \leq i \leq s$. We claim that

$$I_i := P_i + \bigcap_{j \neq i} P_j = R.$$

Notice that $P_i \subseteq I_i \subseteq R$. Since P_i is a maximal ideal by part (1), we either have $I_i = P_i$ or $I_i = R$. Suppose towards a contradiction that $I_i = P_i$, and recall the fact that $I + J = I$ if and only if $J \subseteq I$. Then we have

$$\bigcap_{j \neq i} P_j \subseteq P_i,$$

which implies that

$$P_1 P_2 \cdots P_{i-1} P_{i+1} \cdots P_s \subseteq \bigcap_{j \neq i} P_j \subseteq P_i.$$

Using the same argument as the proof of (2), we can show that $P_1 P_2 \cdots P_{i-1} P_{i+1} \cdots P_s$ cannot be contained in the prime ideal P_i as each ideal P_j with $j \neq i$ is prime. This contradicts our assumption that $I_i = P_i$, so we must have $I_i = R$. \square

THEOREM 8.3: SUN-TZU

Let R be a ring, and let I_1, \dots, I_s be two-sided ideals of R such that

- (i) $\bigcap_{j=1}^s I_j = (0)$, and
- (ii) for all $i = 1, \dots, s$, we have $I_i + \bigcap_{j \neq i} I_j = R$.

Then we have

$$R \cong \prod_{i=1}^s R/I_i.$$

PROOF. For $i = 1, \dots, s$, we have a canonical surjection

$$\begin{aligned}\pi_i : R &\rightarrow R/I_i \\ r &\mapsto r + I_i,\end{aligned}$$

which is a ring homomorphism. We define

$$\begin{aligned}\Psi : R &\rightarrow R/I_1 \times \cdots \times R/I_s \\ r &\mapsto (\pi_1(r), \dots, \pi_s(r)).\end{aligned}$$

Note that since π_1, \dots, π_s are ring homomorphisms, Ψ is also a ring homomorphism. We now show that Ψ is an isomorphism. Notice that

$$\ker \Psi = \{r \in R : \Psi(r) = 0\} = \{r \in R : \pi_1(r) = \cdots = \pi_s(r) = 0\} = \bigcap_{j=1}^s I_j = (0)$$

where the last equality follows from (i), so Ψ is injective. Now, fix $1 \leq i \leq s$. By (ii), we have

$$I_i + \bigcap_{j \neq i} I_j = R,$$

so we can find $a_i \in I_i$ and $b_i \in \bigcap_{j \neq i} I_j$ such that $a_i + b_i = 1$. We can write $b_i = 1 - a_i$, so we find that

$$\pi_i(b_i) = \pi_i(1) - \pi_i(a_i) = (1 + I_i) - (0 + I_i) = 1 + I_i$$

since $a_i \in I_i$. On the other hand, when $n \neq i$, we have $b_i \in \bigcap_{j \neq i} I_j \subseteq I_n$, which gives $\pi_n(b_i) = 0 + I_n$. It follows that

$$\begin{aligned}\Psi(b_i) &= (\pi_1(b_i), \pi_2(b_i), \dots, \pi_i(b_i), \dots, \pi_s(b_i)) \\ &= (0 + I_1, 0 + I_2, \dots, 0 + I_{i-1}, 1 + I_i, 0 + I_{i+1}, \dots, 0 + I_s).\end{aligned}$$

Therefore, given $r_1, \dots, r_s \in R$, we have $r = r_1 b_1 + \cdots + r_s b_s \in R$, and we see that

$$\Psi(r) = \Psi(r_1 b_1 + \cdots + r_s b_s) = \Psi(r_1 + I_1, \dots, r_s + I_s).$$

We conclude that Ψ is surjective, so it is an isomorphism, as required. \square

THEOREM 8.4: ARTIN-WEDDERBURN

Let R be a left Artinian ring. If R has no nonzero nil ideals, then there exists $s \geq 1$, division rings D_1, \dots, D_s , and integers $n_1, \dots, n_s \geq 1$ such that

$$R \cong \prod_{i=1}^s M_{n_i}(D_i).$$

PROOF. Let R be a left Artinian ring with no nonzero nil ideals. We showed in Lemma 8.1 that R has finitely many prime ideals; call them P_1, \dots, P_s . Moreover, observe that $\bigcap_{j=1}^s P_j$ is a nil ideal by Theorem 7.10, and since R has no nonzero nil ideals, it must be that $\bigcap_{j=1}^s P_j = (0)$. We also showed that $P_i + \bigcap_{j \neq i} P_j = R$ for all $i = 1, \dots, s$ in Lemma 8.2. It follows from Sun-tzu that

$$R \cong \prod_{i=1}^s R/P_i.$$

We know that R/P_i is a prime left Artinian ring by Remark 8.1, so Theorem 6.5 implies that $R/P_i \cong M_{n_i}(D_i)$ for some $n_i \geq 1$ and division ring D_i . Thus, we conclude that

$$R \cong \prod_{i=1}^s R/P_i \cong \prod_{i=1}^s M_{n_i}(D_i). \quad \square$$

9 Corollary of Sun-tzu, Maschke's theorem (09/27/2021)

Let's first look at a corollary of Sun-tzu (Theorem 8.3).

REMARK 9.1

Let k be a field. If R is a k -algebra, then each canonical surjection $\pi_i : R \rightarrow R/I_i$ in the proof of Sun-tzu is a k -algebra homomorphism, which means that the map $\Psi : R \rightarrow R/I_1 \times \cdots \times R/I_s$ is also a k -algebra homomorphism.

COROLLARY 9.2

Let k be an algebraically closed field, and let R be a finite-dimensional k -algebra with no nonzero nil ideals. Then we have

$$R \cong \prod_{i=1}^s M_{n_i}(k)$$

for some $s \geq 1$ and integers $n_1, \dots, n_s \geq 1$.

PROOF. Since R is a finite-dimensional k -algebra, we see that R is left Artinian (Remark 5.7). Hence, R has only finitely many prime ideals (Lemma 8.2), say P_1, \dots, P_s . Moreover, since R has no nonzero nil ideals, we have $\bigcap_{j=1}^s P_j = (0)$ (Theorem 7.10), and $P_i + \bigcap_{j \neq i} P_j = R$ for all $i = 1, \dots, s$ since R is left Artinian (Lemma 8.2). By Sun-tzu, we have

$$R \cong R/P_1 \times \cdots \times R/P_s.$$

Then, since k is algebraically closed and each R/P_i is a prime finite-dimensional k -algebra, Corollary 7.4 implies that

$$R \cong R/P_1 \times \cdots \times R/P_s \cong M_{n_1}(k) \times \cdots \times M_{n_s}(k). \quad \square$$

Now that we have the Artin-Wedderburn theorem in our toolkit, we can finally get started with some representation theory. Let G be a finite group with $|G| = n$, and let k be an algebraically closed field. Recall that $V := k[G]$ is the group algebra of the group G over the field k , with $\dim_k k[G] = |G| = n$. Moreover, we have the embedding

$$\Phi : k[G] \rightarrow \text{End}_k(V) \cong M_n(k),$$

where we send each $g \in G$ to the left multiplication map

$$\begin{aligned} L_g : V &\rightarrow V \\ x &\mapsto g \cdot x \end{aligned}$$

and extend linearly over k . We call this the **left regular representation** of G .

Next, let's recall some linear algebra. Let W be a vector space with basis $\mathcal{B} = \{w_1, \dots, w_n\}$, and let $T : W \rightarrow W$ be a linear map. Then we can define a matrix $[T]_{\mathcal{B}}$ by setting $[T]_{\mathcal{B}} = (c_{ij})$ where

$$Tw_j = \sum_{i=1}^n c_{ij} w_i.$$

Observe that the trace of T is given by

$$\text{Tr}(T) = \sum_{j=1}^n c_{jj},$$

which is the sum of the coefficients of w_j in Tw_j (and this is independent of the basis \mathcal{B}).

Now, for the map $L_g : V \rightarrow V$ with $g \in G$, what is $\text{Tr}(L_g)$? First, note that the elements of G form a basis over $V = k[G]$; that is, we have $\mathcal{B} = \{g_1, \dots, g_n\} = G$ in this case. Observe that

$$L_g(g_i) = g \cdot g_i = 1 \cdot g \cdot g_i + \sum_{h \in G \setminus \{gg_i\}} 0 \cdot h. \quad (9.1)$$

For $j = 1, \dots, n$, the coefficient of g_j in gg_j is 1 if $g = 1$, and 0 if $g \neq 1$. Indeed, if $g \neq 1$, then g_j would be different than gg_j , so it would have coefficient 0 in equation (9.1). This implies that

$$\text{Tr}(L_g) = \sum_{j=1}^n \begin{cases} 1 & \text{if } g = 1 \\ 0 & \text{if } g \neq 1 \end{cases} = \begin{cases} n & \text{if } g = 1 \\ 0 & \text{if } g \neq 1. \end{cases}$$

THEOREM 9.3: MASCHKE

Let k be a field (not necessarily algebraically closed), and let G be a finite group. If $\text{char}(k) \nmid |G|$, then $k[G]$ has no nonzero nil ideals.

PROOF. Suppose towards a contradiction that $k[G]$ has a nonzero nil two-sided ideal N . Pick a nonzero element

$$x = \sum_{g \in G} \alpha_g g \in N.$$

Since x is nonzero, there exists some $g_0 \in G$ such that $\alpha_{g_0} \neq 0$. As N is an ideal of $k[G]$, we also have $x \cdot g_0^{-1} \in N$. The coefficient of 1 in $x \cdot g_0^{-1}$ is $\alpha_{g_0} \neq 0$. Thus, we can assume without loss of generality that $x = \sum_{g \in G} \alpha_g g \in N$ has $\alpha_1 \neq 0$.

Let $A \in M_n(k)$ be nilpotent so that $A^n = 0$. Let v be an eigenvector of A with eigenvalue λ . Then we have

$$Av = \lambda v \implies A^2v = \lambda^2v \implies \dots \implies A^nv = \lambda^nv,$$

which implies that $\lambda = 0$ since $A^n = 0$. In particular, $\text{Tr}(A)$ is the sum of the eigenvalues of A (with multiplicity), and the above argument shows that all the eigenvalues of A are 0, so $\text{Tr}(A) = 0$.

Now, consider the injective k -algebra homomorphism

$$\Phi : k[G] \rightarrow \text{End}_k(V) \cong M_n(k) : \sum_{g \in G} \beta_g \cdot g \mapsto \sum_{g \in G} \beta_g \cdot L_g$$

we discussed at the beginning of this lecture (the left regular representation of G). We had an element

$$x = \sum_{g \in G} \alpha_g g \in N$$

with $\alpha_1 \neq 0$. Note that x is nilpotent since N is a nil ideal; say $x^j = 0$ for some $j \geq 1$. Then we have

$$\Phi(x)^j = \Phi(x^j) = \Phi(0) = 0,$$

so $\Phi(x)$ is also nilpotent. Our discussion above implies that $\text{Tr}(\Phi(x)) = 0$. However, we also see that

$$\text{Tr}(\Phi(x)) = \text{Tr} \left(\sum_{g \in G} \alpha_g \cdot L_g \right) = \sum_{g \in G} \alpha_g \cdot \text{Tr}(L_g) = |G| \cdot \alpha_1 \neq 0$$

since $\alpha_1 \neq 0$ and $\text{char}(k) \nmid |G|$. This is a contradiction, so $k[G]$ has no nonzero nil ideals. \square

REMARK 9.4

Question 1 of Assignment 1 shows that the converse of Maschke's theorem also holds. Indeed, we proved that if $\text{char}(k) \mid |G|$, then $k[G]u$ is a nonzero nil ideal where $u = \sum_{g \in G} g$.

COROLLARY 9.5

Let k be an algebraically closed field, and let G be a finite group. If $\text{char}(k) \nmid |G|$, then there exists $s \geq 1$ and integers $n_1, \dots, n_s \geq 1$ such that

$$k[G] \cong M_{n_1}(k) \times \cdots \times M_{n_s}(k).$$

PROOF. By Maschke's theorem, we know that $k[G]$ has no nonzero nil ideals, and it is left Artinian as it is a finite-dimensional k -algebra. Since k is algebraically closed, it follows that

$$k[G] \cong M_{n_1}(k) \times \cdots \times M_{n_s}(k)$$

for some $s \geq 1$ and integers $n_1, \dots, n_s \geq 1$ by Corollary 9.2. □

This corollary is important because this gives us a nice relationship between $k[G]$, which is something intrinsic to the group G , and the direct product of matrix rings, which is more in the realm of linear algebra.

10 Class functions, abelianization of a group (09/29/2021)

By Corollary 9.5, we know that if k is algebraically closed, G is a finite group, and $\text{char}(k) \nmid |G|$, then

$$k[G] \cong M_{n_1}(k) \times \cdots \times M_{n_s}(k)$$

for some $s \geq 1$ and integers $n_1, \dots, n_s \geq 1$. This will be our setting for this lecture, and we'll derive more properties about the choice of $s \geq 1$ and the integers $n_1, \dots, n_s \geq 1$.

THEOREM 10.1

We have $|G| = n_1^2 + \cdots + n_s^2$.

PROOF. The isomorphism in Corollary 9.5 is a k -algebra isomorphism, so we find that

$$\begin{aligned} |G| &= \dim_k k[G] \\ &= \dim_k M_{n_1}(k) \times \cdots \times M_{n_s}(k) \\ &= \dim_k M_{n_1}(k) + \cdots + \dim_k M_{n_s}(k) \\ &= n_1^2 + \cdots + n_s^2. \end{aligned} \quad \square$$

Next, we'll work towards showing that s is the number of conjugacy classes of G .

REMARK 10.2

If R is a k -algebra, then $Z(R)$ is also a k -algebra. Indeed, we have an embedding $k \hookrightarrow Z(R) \subseteq R$ which sends 1_k to 1_R , and this also gives us an embedding $k \hookrightarrow Z(Z(R)) = Z(R)$.

REMARK 10.3

If T_1, \dots, T_s are rings, then

$$Z(T_1 \times \cdots \times T_s) = Z(T_1) \times \cdots \times Z(T_s).$$

PROPOSITION 10.4

We have $Z(M_n(k)) = kI_n = \{\lambda I_n : \lambda \in k\}$.

PROOF. We'll give two proofs: an elementary one, and a high level one.

For the elementary proof, suppose that $(a_{ij}) \in Z(M_n(k))$. Then observe that

$$\begin{aligned} \begin{pmatrix} a_{11} & 0 & \cdots & 0 \\ a_{21} & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & 0 & \cdots & 0 \end{pmatrix} &= \begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{pmatrix} \begin{pmatrix} 1 & 0 & \cdots & 0 \\ 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 0 \end{pmatrix} \\ &= \begin{pmatrix} 1 & 0 & \cdots & 0 \\ 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 0 \end{pmatrix} \begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{pmatrix} \\ &= \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 0 \end{pmatrix}. \end{aligned}$$

In particular, we have $a_{21} = \cdots = a_{n1} = 0$ and $a_{12} = \cdots = a_{1n} = 0$, which shows that

$$A = \left(\begin{array}{c|ccc} a_{11} & 0 & \cdots & 0 \\ \hline 0 & & & \\ \vdots & & A' & \\ 0 & & & \end{array} \right)$$

for some smaller matrix A' . The argument follows inductively.

For a high level proof (where k is algebraically closed), take $R = M_n(k)$ and consider the simple left R -module

$$M = k^{n \times 1} = \left\{ \begin{pmatrix} \lambda_1 \\ \vdots \\ \lambda_n \end{pmatrix} : \lambda_1, \dots, \lambda_n \in k \right\}.$$

We have shown that $\Delta = \text{End}_R(M) \cong k$ by identifying each $\lambda \in k$ with the map

$$\begin{aligned} \Phi_\lambda : M &\rightarrow M \\ v &\mapsto \lambda \cdot v. \end{aligned}$$

Now, if $A \in Z(M_n(k))$, then the map

$$\begin{aligned} f : M &\rightarrow M \\ v &\mapsto Av \end{aligned}$$

is R -linear; indeed, for $B \in M_n(k) = R$ and $v_1, v_2 \in M$, we have

$$\begin{aligned} f(Bv_1 + v_2) &= A(Bv_1 + v_2) \\ &= ABv_1 + Av_2 \\ &= BAv_1 + Av_2 \\ &= Bf(v_1) + f(v_2). \end{aligned}$$

In particular, we see that $f \in \Delta$, so $f = \Phi_\gamma$ for some $\gamma \in k$. Then $f(v) = Av = \gamma v$ for all $v \in M$, which implies that $A = \gamma I$. \square

Combining Proposition 10.4 with Remark 10.3, we see that

$$\begin{aligned} Z(M_{n_1}(k) \times M_{n_s}(k)) &= Z(M_{n_1}(k)) \times \cdots \times Z(M_{n_s}(k)) \\ &= \{(\lambda_1 I_{n_1}, \dots, \lambda_s I_{n_s}) : (\lambda_1, \dots, \lambda_s) \in k^s\}. \end{aligned}$$

In particular, we have $\dim_k Z(k[G]) = \dim_k Z(M_{n_1}(k) \times \cdots \times M_{n_s}(k)) = s$.

DEFINITION 10.5

We say that a function $\alpha : G \rightarrow k$ is a **class function** if α is constant when restricted to each conjugacy class of G .

LEMMA 10.6

Let $\alpha : G \rightarrow k$ be a function. Then $z := \sum_{g \in G} \alpha(g)g$ is central in $k[G]$ if and only if α is a class function.

PROOF. Note that $z \in \sum_{g \in G} \alpha(g)g$ is in $Z(k[G])$ if and only if $xz = zx$ for all $x \in G$; the backwards direction here is because G forms a basis for $k[G]$. This occurs if and only if $z = x^{-1}zx$ for all $x \in G$ by rearranging. Now, this is equivalent to

$$\sum_{g \in G} \alpha(g)g = x^{-1} \left(\sum_{g \in G} \alpha(g)g \right) x = \sum_{g \in G} \alpha(g)x^{-1}gx = \sum_{h \in G} \alpha(xhx^{-1})h$$

holding for all $x \in G$, where the last equality follows from making the substitution $h = x^{-1}gx$. This is true if and only if the coefficient of the left-hand side is the same as the coefficient of the right-hand side. That is, $\alpha(h) = \alpha(xhx^{-1})$ for all $h \in G$ and $x \in G$, and this is exactly the definition of a class function. \square

Let G be a finite group, and let $\mathcal{C}_1, \dots, \mathcal{C}_s$ be the conjugacy classes of G . For $i = 1, \dots, s$, observe that

$$\alpha(g) = \begin{cases} 1 & \text{if } g \in \mathcal{C}_i \\ 0 & \text{if } g \notin \mathcal{C}_i \end{cases}$$

is a class function. Then the elements

$$z_i = \sum_{g \in G} \alpha(g)g = \sum_{g \in \mathcal{C}_i} g$$

for $i = 1, \dots, s$ are central by Lemma 10.6.

PROPOSITION 10.7

Let G be a finite group with conjugacy classes $\mathcal{C}_1, \dots, \mathcal{C}_s$. Then the elements

$$z_i := \sum_{g \in \mathcal{C}_i} g$$

for $i = 1, \dots, s$ form a basis for $Z(k[G])$.

PROOF. We have already seen that the z_i are central. To show linear independence, suppose that

$$c_1 z_1 + \dots + c_s z_s = 0,$$

where we take 0 to mean $\sum_{g \in G} 0 \cdot g$ in $k[G]$. If $g \in \mathcal{C}_i$, then the coefficient of g on the left-hand side is c_i . But the coefficient on the right-hand side is always 0, so $c_1 = \dots = c_s = 0$. To see that $\{z_1, \dots, z_s\}$ spans $Z(k[G])$, recall that $z \in \sum_{g \in G} \alpha(g)g \in Z(k[G])$ if and only if α is a class function. Let β_i be the unique value of α on \mathcal{C}_i . Then we see that

$$z = \sum_{g \in G} \alpha(g)g = \sum_{i=1}^s \sum_{g \in \mathcal{C}_i} \alpha(g)g = \sum_{i=1}^s \beta_i \sum_{g \in \mathcal{C}_i} g = \sum_{i=1}^s \beta_i z_i,$$

so we can write z as a linear combination of the z_i , completing the proof. \square

THEOREM 10.8

In the setting of Corollary 9.5, s is the number of conjugacy classes of G .

PROOF. We previously showed that $\dim_k Z(k[G]) = \dim_k Z(M_{n_1}(k) \times \dots \times M_{n_s}(k)) = s$. Proposition 10.7 tells us that $\dim_k Z(k[G])$ is the number of conjugacy classes of G . \square

For the remainder of the lecture, we recall the abelianization of a group G . We denote by G' the commutator (or derived) subgroup of G , which is the smallest subgroup of G which contains all elements of the form $ghg^{-1}h^{-1}$ with $g, h \in G$ (we call these elements commutators).

Note that G/G' is abelian. Indeed, take $g, h \in G$ so that $gG', hG' \in G/G'$. Observe that

$$(h^{-1})(g^{-1})(h^{-1})^{-1}(g^{-1})^{-1} = h^{-1}g^{-1}hg \in G',$$

so we have

$$(gG')(hG') = ghG' = gh(h^{-1}g^{-1}hg)G' = hgG' = (hG')(gG').$$

For this reason, we call G/G' the **abelianization** of G .

EXERCISE 10.9

Show that G/G' has the universal property that if A is abelian group, $\phi : G \rightarrow A$ is a group homomorphism, and $\pi : G \rightarrow G/G'$ is the canonical quotient map, then there is a unique group homomorphism $\Phi : G/G' \rightarrow A$ such that $\Phi \circ \pi = \phi$.

$$\begin{array}{ccc} G & \xrightarrow{\phi} & A \\ \pi \downarrow & \nearrow \Phi & \\ G/G' & & \end{array}$$

11 Applications of the big theorem, representations (10/01/2021)

There is a similar notion of abelianization for rings. Let R be a ring. The **commutator ideal** $[R, R]$ is the smallest ideal containing all elements of the form $ab - ba$ where $a, b \in R$. We can also think of $[R, R]$ as the intersection of all two-sided ideals J such that $ab - ba \in J$ for all $a, b \in R$.

REMARK 11.1

- (1) Note that $R/[R, R]$ is commutative because for all $a, b \in R$, we have

$$\begin{aligned} (a + [R, R])(b + [R, R]) &= ab + [R, R] \\ &= ab + (ba - ab) + [R, R] \\ &= ba + [R, R] \\ &= (b + [R, R])(a + [R, R]). \end{aligned}$$

- (2) We also have a universal property here; if R is a ring, C is a commutative ring, $\phi : R \rightarrow C$ is a ring homomorphism, and $\pi : R \rightarrow R/[R, R]$ is the canonical quotient map, then there exists a unique ring homomorphism $\Phi : R/[R, R] \rightarrow C$ such that $\Phi \circ \pi = \phi$.

$$\begin{array}{ccc} R & \xrightarrow{\phi} & C \\ \pi \downarrow & \searrow \Phi & \\ R/[R, R] & & \end{array}$$

In Assignment 3, we will prove the following results.

- (1) If k is a field and G is a group, then there is a k -algebra homomorphism

$$k[G]/[k[G], k[G]] \cong k[G/G'].$$

Said another way, the abelianization of the group algebra is isomorphic to the group algebra of the abelianization.

- (2) If $R = M_{n_1}(k) \times \cdots \times M_{n_s}(k)$, then

$$R/[R, R] \cong k^t,$$

where $t = \#\{i : n_i = 1\}$.

As an immediate consequence of these results, we have the following corollary.

COROLLARY 11.2

If $k[G] \cong M_{n_1}(k) \times \cdots \times M_{n_s}(k)$, then $|G/G'| = \#\{i : n_i = 1\}$.

PROOF. Since $k[G]$ and $M_{n_1}(k) \times \cdots \times M_{n_s}(k)$ are isomorphic, so are their abelianizations. It follows that there is a k -algebra homomorphism

$$k[G/G'] \cong k^t$$

where $t = \#\{i : n_i = 1\}$. By looking at the dimensions, we see that

$$|G/G'| = \dim_k k[G/G'] = \dim_k k^t = t = \#\{i : n_i = 1\}. \quad \square$$

EXAMPLE 11.3

Let's look at $\mathbb{C}[S_4]$. Recall that the conjugacy classes of S_n are just sets of permutations with the same disjoint cycle structure. For $n = 4$, the conjugacy classes are

$$[(1)(2)(3)(4)], [(12)(3)(4)], [(12)(34)], [(123)(4)], [(1234)].$$

Notice that we can think of these as

$$1 + 1 + 1 + 1 = 4, 2 + 1 + 1 = 4, 2 + 2 = 4, 3 + 1 = 4, 4 = 4.$$

In particular, there is a bijective correspondence between the conjugacy classes of S_n and the partitions of n .

We can look at the sizes of the conjugacy classes. We have

$$\begin{aligned}\#[(1)(2)(3)(4)] &= 1, \\ \#[(1)(2)(34)] &= 6, \\ \#[(1)(234)] &= 8, \\ \#[(1234)] &= 6, \\ \#[(12)(34)] &= 3.\end{aligned}$$

Since there are 5 conjugacy classes of S_4 , we have

$$\mathbb{C}[S_4] \cong M_{n_1}(\mathbb{C}) \times \cdots \times M_{n_5}(\mathbb{C})$$

for some integers $n_1, \dots, n_5 \geq 1$.

We claim that $S'_4 = A_4$. First, note that $S'_4 \subseteq A_4$ since S'_4/A_4 is abelian. Now, notice that

$$(123) = (12)(13)(12)(13) = (12)(13)(12)^{-1}(13)^{-1} \in S'_4.$$

Therefore, every 3-cycle is in S'_4 as normal subgroups are unions of conjugacy classes. Hence, we see that

$$|S'_4| \geq 9 = \#[(1)(234)] + \#[(1)(2)(3)(4)].$$

Since $|S'_4| \mid |S_4| = 24$ by Lagrange's theorem, we obtain $|S'_4| = 12$, and so $S'_4 = A_4$. From this, we have

$$\#\{i : n_i = 1\} = |S_4/S'_4| = |S_4/A_4| = 2.$$

Now, we have $n_3, n_4, n_5 \geq 2$ with $n_3^2 + n_4^2 + n_5^2 = 22$. The only solution to this is $2^2 + 3^2 + 3^2 = 22$, so we conclude that

$$\mathbb{C}[S_4] \cong \mathbb{C} \times \mathbb{C} \times M_2(\mathbb{C}) \times M_3(\mathbb{C}) \times M_3(\mathbb{C}).$$

EXAMPLE 11.4

If A is abelian with $|A| = n$, then $|A/A'| = n$ so that $\#\{i : n_i = 1\} = n$. It follows that

$$\mathbb{C}[A] \cong \mathbb{C}^n.$$

We can give an alternate argument: if we had $n_i \geq 2$ for some $i = 1, \dots, s$, then the product of matrix rings is no longer commutative, which is a contradiction since $\mathbb{C}[A]$ is commutative.

EXAMPLE 11.5

Let D_5 be the dihedral group of order 10. We can write

$$D_5 = \langle x, y : x^2 = 1, y^5 = 1, xyx = y^{-1} \rangle.$$

We have an isomorphism

$$\mathbb{C}(D_5) \cong M_{n_1}(\mathbb{C}) \times \cdots \times M_{n_s}(\mathbb{C})$$

for some $s \geq 1$ and integers $n_1, \dots, n_s \geq 1$. Notice that

$$10 = 1^2 + 3^2 = 1^2 + 1^2 + 2^2 + 2^2 = \underbrace{1^2 + \cdots + 1^2}_6 + 2^2 = \underbrace{1^2 + \cdots + 1^2}_{10}.$$

One can check that D_5 has 4 conjugacy classes. Therefore, only the choice $10 = 1^2 + 1^2 + 2^2 + 2^2$ works, and we must have

$$\mathbb{C}(D_5) \cong \mathbb{C} \times \mathbb{C} \times M_2(\mathbb{C}) \times M_2(\mathbb{C}).$$

Let's now study representations. Let G be a group and let k be an algebraically closed field such that $\text{char}(k) \nmid |G|$. A **representation** of G is a group homomorphism

$$\rho : G \rightarrow \text{GL}_n(k).$$

REMARK 11.6

The group homomorphism $\rho : G \rightarrow \text{GL}_n(k)$ extends to a k -algebra homomorphism

$$\tilde{\rho} : k[G] \rightarrow M_n(k).$$

Conversely, if $\phi : k[G] \rightarrow M_n(k)$ is a k -algebra homomorphism, then ϕ restricted to G is a map

$$\phi|_G : G \rightarrow \text{GL}_n(k).$$

This is because $\phi(1) = I$, so for any $g \in G$, we have

$$\phi(g) \cdot \phi(g)^{-1} = \phi(g \cdot g^{-1}) = \phi(1) = I.$$

Thus, $\phi(g)$ must be an invertible matrix. Moreover, $\tilde{\rho}|_G = \rho$.

REMARK 11.7

If $\phi : k[G] \rightarrow M_n(k)$ is a k -algebra homomorphism, then

$$V = k^{n \times 1} = \left\{ \begin{pmatrix} a_1 \\ \vdots \\ a_n \end{pmatrix} : a_1, \dots, a_n \in k \right\}$$

can be given a left $k[G]$ -module structure with the rule

$$r \cdot v := \phi(r) \cdot v$$

for $r \in k[G]$ and $v \in V$.

Notice that if V is a $k[G]$ -module, then we have a k -algebra homomorphism

$$\Psi : k[G] \rightarrow \text{End}_k(V)$$

where we send each $g \in G$ to the map

$$\begin{aligned} L_g : V &\rightarrow V \\ v &\mapsto g \cdot v \end{aligned}$$

and extend linearly over k . In particular,

$$\Psi|_G : G \rightarrow \text{GL}(V) \cong \text{GL}_n(k),$$

where $\text{GL}(V)$ denotes the invertible linear transformations over M . For this reason, if V is a $k[G]$ -module, we will call V a **representation** of G .

12 Direct sums, decompositions of modules (10/04/2021)

We'll first make some definitions.

DEFINITION 12.1

Let V and W be $k[G]$ -modules; that is, they are representations of G .

- (1) If V is simple, we say that V is a **irreducible representation** (or an **irrep**).
- (2) If $W \subseteq V$ is a $k[G]$ -submodule of V , we say that W is a **subrepresentation** of G .
- (3) We call two representations V and W **equivalent** if $V \cong W$ as left $k[G]$ -modules.
- (4) We say that V is **decomposable** if $V = V_1 \oplus V_2$, where V_1 and V_2 are proper submodules of V .

Let's define what a direct sum is. First, let M be an R -module. If M_1 and M_2 are submodules of M , then

$$M_1 + M_2 = \{m_1 + m_2 : m_1 \in M_1, m_2 \in M_2\} \subseteq M.$$

More generally, if we have a family $(M_\alpha)_\alpha \in X$ of submodules of M , then

$$\sum_{\alpha \in X} M_\alpha = \left\{ \sum_{\alpha \in X} m_\alpha : m_\alpha \in M_\alpha, m_\alpha = 0 \text{ for all but finitely many } \alpha \right\} \subseteq M.$$

Then, we call $\sum_{\alpha \in X} M_\alpha \subseteq M$ **direct** when $\sum_{\alpha \in X} m_\alpha = 0$ if and only if $m_\alpha = 0$ for all $\alpha \in X$. In the case where $\sum_{\alpha \in X} M_\alpha$ is a direct sum, we write

$$\bigoplus_{\alpha \in X} M_\alpha := \sum_{\alpha \in X} M_\alpha.$$

REMARK 12.2

Let M be an R -modules, and let M_1 and M_2 be submodules of M . Then $M_1 + M_2$ is a direct sum if and only if $M_1 \cap M_2 = (0)$.

EXAMPLE 12.3

Let V be a vector space over a field k , and let $v_1, v_2 \in V \setminus \{0\}$. Consider the submodules $V_1 = \{\lambda v_1 : \lambda \in k\}$ and $V_2 = \{\lambda v_2 : \lambda \in k\}$. Then $V_1 + V_2$ is a direct sum if and only if v_1 and v_2 are linearly independent.

We'll study some module theory for the group algebra $k[G]$. Let k be an algebraically closed field such that $\text{char}(k) \nmid |G|$.

In the next few lectures, we will work towards proving the following theorem.

THEOREM 12.4

Suppose that

$$k[G] \cong M_{n_1}(k) \times \cdots \times M_{n_s}(k),$$

where s is the number of conjugacy classes of G .

- (1) Up to isomorphism, $k[G]$ has s pairwise non-isomorphic simple left modules V_1, \dots, V_s (that is, s pairwise inequivalent irreducible representations).
- (2) Every $k[G]$ -module decomposes as a direct sum of copies of V_1, \dots, V_s .
- (3) **Uniqueness:** If $V_1^{a_1} \oplus V_2^{a_2} \oplus \cdots \oplus V_s^{a_s} \cong V_1^{b_1} \oplus V_2^{b_2} \oplus \cdots \oplus V_s^{b_s}$, then $a_i = b_i$ for all $i = 1, \dots, s$, where by V^a , we mean $V^a := V \oplus \cdots \oplus V$ (a times).

What is the significance of this theorem? First, let's ask what the V_i 's are. We know that

$$k[G] \cong M_{n_1}(k) \times \cdots \times M_{n_s}(k),$$

and for each $i = 1, \dots, s$, we have the projection

$$\pi_i : M_{n_1}(k) \times \cdots \times M_{n_s}(k) \rightarrow M_{n_i}(k).$$

Note that $M_{n_i}(k)$ has the module $V_i \cong k^{n_i \times 1}$. Now, if V is a representation of G which looks like

$$V = V_{i_1} \oplus \cdots \oplus V_{i_q},$$

we recall that $k[G]$ acting on V gives us a representation

$$\rho : G \rightarrow \text{GL}(V)$$

given by $\rho(g)(v) := g \cdot v$. Now, what's the significance of the decomposition of V above? Suppose for simplicity that we had $V = W_1 \oplus W_2$, where W_1 and W_2 are $k[G]$ -submodules of V . Let $\{v_1, \dots, v_d\}$ be a basis for W_1 , and let $\{v_{d+1}, \dots, v_n\}$ be a basis for W_2 . Then we have

$$\rho(g)(v_j) = g \cdot v_j = \begin{cases} a_{1j}v_1 + \cdots + a_{dj}v_d, & \text{if } j \leq d, \\ a_{(d+1)j}v_{d+1} + \cdots + a_{nj}v_n, & \text{if } d+1 \leq j \leq n. \end{cases}$$

In particular, by setting $\mathcal{B} = \{v_1, \dots, v_n\}$, we see that

$$[\rho(g)]_{\mathcal{B}} = \left(\begin{array}{c|c} A_1 & 0 \\ \hline 0 & A_2 \end{array} \right),$$

where A_1 is a $d \times d$ matrix and A_2 is an $(n-d) \times (n-d)$ matrix. Therefore, the importance of the theorem is that if we are given a finite-dimensional representation, we can uniquely write it as a block diagonal matrix

(up to ordering of the blocks), where the blocks are representations coming from the irreducibles $V_i \cong k^{n_i \times 1}$. Therefore, if we understand irreducibles, then we understand every representation.

First, in order to understand $k[G]$, we looked at Artinian rings with no nonzero nil ideals. Now that we understand $k[G]$, our main goal is to understand representations. Our discussion above shows that it suffices to understand the simples $V_i \cong k^{n_i \times 1}$. We will use character theory to do so, which we will get to soon, and we'll understand everything.

Due to the isomorphism

$$k[G] \cong M_{n_1}(k) \times \cdots \times M_{n_s}(k),$$

we can just think of $k[G]$ as a product of matrix rings. Therefore, it suffices to understand the left modules of $M_{n_1}(k) \times \cdots \times M_{n_s}(k)$ to know the left modules of $k[G]$. Let R and S be rings with an isomorphism $\phi : R \rightarrow S$. If we have an R -module M , we obtain an S -module by taking

$$s \cdot m := \phi^{-1}(s) \cdot m.$$

Conversely, if N is a left S -module, then we can give it an R -module structure by

$$r \cdot n = \phi(r) \cdot n.$$

That is, the isomorphism ϕ is just a way of relabelling these elements.

LEMMA 12.5

Let $R = M_{n_1}(k) \times \cdots \times M_{n_s}(k)$, and let $V_i = k^{n_i \times 1}$ for each $i = 1, \dots, s$. For each $i = 1, \dots, s$ we define

$$(A_1, \dots, A_i, \dots, A_s) \cdot v := A_i v$$

where $(A_1, A_2, \dots, A_s) \in R$ and $v \in V_i$. Then V_i is a simple left R -module, and if $i \neq j$, then $V_i \not\cong V_j$.

PROOF. If $(A_1, \dots, A_s), (B_1, \dots, B_s) \in R$ and $v \in V_i$, then

$$\begin{aligned} (A_1, \dots, A_i, \dots, A_s) \cdot (B_1, \dots, B_i, \dots, B_s) \cdot v &= (A_1 B_1, \dots, A_i B_i, \dots, A_s B_s) v \\ &= A_i B_i v \\ &= A_i (B_i v) \\ &= (A_1, \dots, A_s) [(B_1, \dots, B_s) \cdot v] \end{aligned}$$

Therefore, V_i is a left R -module; the other properties come for free since V_i is already a module over $M_{n_i}(k)$, and hence it is an abelian group.

Why is V_i simple as an R -module? Notice that it suffices to show that if $v_1 \in V_i \setminus \{0\}$ and $v_2 \in V_i$, then there exists $r \in R$ such that $r \cdot v_1 = v_2$. Indeed, if V_i is simple, then the only submodules are (0) and V_i itself. If we have a nonzero element of V_i , then it should generate all of V_i .

We already know that V_i is a simple $M_{n_i}(k)$ -module. Therefore, there exists $A \in M_{n_i}(k)$ such that $A v_1 = v_2$. Let $r = (0, \dots, 0, A, 0, \dots, 0)$, where A is located at the i -th coordinate. Then $r \cdot v_1 = v_2$, so V_i is a simple left R -module.

Next, we show that if $i \neq j$, then $V_i \not\cong V_j$ as left R -modules. Suppose that we have an R -linear isomorphism $f : V_i \rightarrow V_j$. If $v \in V_i$, then

$$f((0, \dots, 0, I, 0, \dots, 0) \cdot v) = f(0 \cdot v) = 0 \in V_j,$$

where I is in the j -th position, and the i -th position is one of the zeros. Since f is R -linear, then

$$f((0, \dots, 0, I, 0, \dots, 0) \cdot v) = (0, \dots, 0, I, 0, \dots, 0) \cdot f(v) = I \cdot f(v) = f(v).$$

This means that f is identically zero, contradicting the fact that it is an isomorphism from V_i to V_j . \square

REMARK 12.6

In fact, we have shown that if $i \neq j$, then

$$\text{Hom}_R(V_i, V_j) = \{0\}.$$

When $i = j$, we have $\text{Hom}_R(V_i, V_j) = \text{End}_R(V_i)$. In the case that k is algebraically closed and R is a finite-dimensional k -algebra, we have $\text{End}_R(V_i) \cong k$ by Proposition 3.1, since V_i is a simple left R -module.

13 Number of inequivalent irreducible representations (10/06/2021)

Last time, we were looking at a ring

$$R = M_{n_1}(k) \times \cdots \times M_{n_s}(k).$$

We saw that $V_i = k^{n_i \times 1}$ is a left R -module with the action

$$(A_1, \dots, A_s) \cdot v := A_i v \in V_i$$

for $(A_1, \dots, A_s) \in R$ and $v \in V_i$. Moreover, V_i is a simple left R -module with $V_i \not\cong V_j$ when $i \neq j$.

Now, we observe that

$$\begin{aligned} \text{Ann}_R(V_i) &= \{(A_1, \dots, A_{i-1}, 0, A_{i+1}, \dots, A_s) : A_j \in M_{n_j}(k)\} \\ &= M_{n_1}(k) \times \cdots \times M_{n_{i-1}}(k) \times \{0\} \times M_{n_{i+1}}(k) \times \cdots \times M_{n_s}(k). \end{aligned}$$

In particular, if $i \neq j$, then $\text{Ann}_R(V_i) \not\cong \text{Ann}_R(V_j)$. Assignment 3 Question 2 then gives us another proof of the fact that $V_i \not\cong V_j$.

DEFINITION 13.1

If R is a ring, we will write ${}_R R$ to mean R considered as a left R -module. (Similarly, the notation R_R means R taken as a right R -module.)

Let $A, B \in M_n(k)$. We can think of B as n columns concatenated with each other. In particular, if v_1, \dots, v_n are the columns of B , then the columns of AB are given by Av_1, \dots, Av_n . Therefore, if $R = M_n(k)$ and $V = k^{n \times 1}$, then

$${}_R R \cong \underbrace{V \oplus \cdots \oplus V}_n$$

with the R -module isomorphism

$$B \mapsto (v_1, \dots, v_n),$$

where as before, v_1, \dots, v_n are the columns of B .

More generally, if $R = M_{n_1}(k) \times \cdots \times M_{n_s}(k)$ and $V_i = k^{n_i \times 1}$, then we have

$$(A_1, \dots, A_s) \cdot v = A_i v$$

for $(A_1, \dots, A_s) \in R$ and $v \in V_i$, so we see that

$${}_R R \cong \underbrace{V_1 \oplus \cdots \oplus V_1}_{n_1} \oplus \underbrace{V_2 \oplus \cdots \oplus V_2}_{n_2} \oplus \cdots \oplus \underbrace{V_s \oplus \cdots \oplus V_s}_{n_s}$$

with the explicit R -module isomorphism

$$(B_1, \dots, B_s) \in {}_R R \mapsto \underbrace{(v_{11}, \dots, v_{1n_1})}_{\in V_1^{n_1}}, \dots, \underbrace{(v_{s1}, \dots, v_{sn_s})}_{\in V_s^{n_s}},$$

where v_{i1}, \dots, v_{in_i} are the columns of B_i for each $i = 1, \dots, s$. Indeed, we can see that this is an R -module isomorphism because for $(A_1, \dots, A_s) \in R$ and $(B_1, \dots, B_s) \in {}_R R$, the columns of $A_i B_i$ are $Av_{i1}, \dots, Av_{in_i}$, and on the other hand, we have

$$(A_1, \dots, A_s) \cdot (v_{11}, \dots, v_{1n_1}, \dots, v_{s1}, \dots, v_{sn_s}) = \underbrace{(A_1 v_{11}, \dots, A_1 v_{1n_1})}_{A_1 B_1}, \dots, \underbrace{(A_s v_{s1}, \dots, A_s v_{sn_s})}_{A_s B_s}.$$

From this discussion, we obtain the key fact that if $R = M_{n_1}(k) \times \dots \times M_{n_s}(k)$ and $V_i = k^{n_i \times 1}$, then

$${}_R R \cong V_1^{n_1} \oplus \dots \oplus V_s^{n_s}$$

as R -modules. Now, we are almost in the position to finish proving Theorem 12.4.

REMARK 13.2

Let N and M_α for $\alpha \in X$ be left R -modules.

(1) From Exercise 4 on Assignment 2, we have

$$\mathrm{Hom}_R \left(\bigoplus_{\alpha \in X} M_\alpha, N \right) \cong \prod_{\alpha \in X} \mathrm{Hom}_R(M_\alpha, N).$$

(2) If $N \neq (0)$ is a left R -module, then

$$\mathrm{Hom}_R(R, N) \neq (0).$$

Notice that for all $n \in N$, there exists a map

$$\begin{aligned} \varphi_n : {}_R R &\rightarrow N \\ r &\mapsto r \cdot n. \end{aligned}$$

For $a \in R$ and $r \in {}_R R$, we have $\varphi_n(ar) = ar \cdot n = a \cdot (rn) = a \cdot \varphi_n(r)$, so φ_n is R -linear. Moreover, when $n \neq 0$, we have $\varphi_n(1) = n \neq 0$, so $\varphi_n \neq 0$.

EXERCISE 13.3

Define the map

$$\begin{aligned} e : \mathrm{Hom}_R({}_R R, N) &\rightarrow N \\ \varphi &\mapsto \varphi(1). \end{aligned}$$

If R is commutative, show that e is an isomorphism of R -modules.

Now, we can prove part (1) of Theorem 12.4.

THEOREM 13.4

Let $R \cong M_{n_1}(k) \times \cdots \times M_{n_s}(k)$ and $V_i \cong k^{n_i \times 1}$. If N is a simple left R -module, then there exists some $i = 1, \dots, s$ such that $N \cong V_i$ as R -modules. In particular, R has exactly s simple left R -modules up to isomorphism.

PROOF. Let N be a simple R -module. Then we have

$$\text{Hom}_R(RR, N) \neq (0)$$

since $N \neq (0)$. In particular, we obtain

$$\text{Hom}_R(RR, N) \cong \text{Hom}_R(V_1^{n_1} \oplus \cdots \oplus V_s^{n_s}, N) \cong \prod_{i=1}^s \text{Hom}_R(V_i, N)^{n_i}.$$

Since $\text{Hom}_R(RR, N) \neq (0)$, there exists $i = 1, \dots, s$ such that $\text{Hom}_R(V_i, N) \neq (0)$. Therefore, there exists a nonzero R -module homomorphism $f : V_i \rightarrow N$. Now, V_i is simple, and since $\ker(f)$ is a submodule of V_i , we either have $\ker(f) = (0)$ or $\ker(f) = V_i$. But f is nonzero, so we have $\ker(f) = (0)$. Similarly, $\text{im}(f)$ is a submodule of N . Again, f is nonzero, so $\text{im}(f) \neq (0)$, and since N is simple, $\text{im}(f) = N$.

As in the proof of Schur's lemma (Theorem 2.15), the set theoretic inverse of f is an R -module homomorphism with $f \circ f^{-1} = \text{id}_N$ and $f^{-1} \circ f = \text{id}_{V_i}$. Therefore, $f : V_i \rightarrow N$ is an R -module isomorphism. \square

Towards proving (2) of Theorem 12.4, we'll first prove the following fact.

PROPOSITION 13.5

Every R -module M satisfies

$$M \cong R^{\oplus X} / L$$

where $R^{\oplus X} = \bigoplus_{x \in X} R$, and L is a submodule of $R^{\oplus X}$.

PROOF. For each $m \in M$, we will define a formal symbol e_m . (We can think of this as a vector $e_m = (0, \dots, 0, 1, 0, \dots, 0)$ where 1 is in the m -th position, but this choice doesn't always work.) Define an R -module homomorphism $\Psi : \bigoplus_{m \in M} Re_m \rightarrow M$ by

$$\sum_{m \in M} r_m e_m \mapsto \sum_{m \in M} r_m \cdot m.$$

We note that these must be finite sums in order to make sense. When $r \in R$, we have

$$\Psi \left(r \cdot \sum_{m \in M} r_m e_m \right) = \Psi \left(\sum_{m \in M} r \cdot r_m e_m \right) = \sum_{m \in M} r \cdot r_m \cdot m = r \cdot \sum_{m \in M} r_m \cdot m = r \cdot \Psi \left(\sum_{m \in M} r_m e_m \right).$$

Therefore, Ψ is R -linear. Moreover, $\Psi(1 \cdot e_m) = m$, so Ψ is onto. Let $L = \ker \Psi$. By the first isomorphism theorem, we obtain $\bigoplus_{m \in M} Re_m / L \cong \text{im } \Psi = M$, and we can take $\bigoplus_{m \in M} Re_m$ as $R^{\oplus X}$. \square

14 Semisimple rings and a characterization (10/08/2021)

DEFINITION 14.1

Let R be a ring. We say that a left R -module M is **semisimple** if M can be written as the direct sum of simple submodules. We say that R is a **(left) semisimple ring** if every left R -module is semisimple.

EXAMPLE 14.2

An example of a non-semisimple ring is \mathbb{Z} . The simple modules are isomorphic to $\mathbb{Z}/p\mathbb{Z}$ for primes p , and we notice that $\mathbb{Z}/4\mathbb{Z}$ cannot be written as the direct sum of simple submodules.

EXAMPLE 14.3

Let k be a field. A k -module is simply a vector space, and a submodule is a subspace. In particular, a simple k -module V is a vector space whose only subspaces are (0) and V itself. Therefore, V is a simple k -module if and only if $\dim_k V = 1$. Now, if W is a k -vector space, then we can write

$$W = \bigoplus_{\alpha \in \mathcal{B}} kv_{\alpha},$$

since every vector space has a basis \mathcal{B} . Hence, k is a semisimple ring.

Notice that the fact that every vector space has a basis relies on Zorn's lemma. The following theorem generalizes this example, and at some point, we'll have to use Zorn's lemma to prove it.

THEOREM 14.4

Let R be a ring. Then R is a (left) semisimple ring if and only if ${}_R R$ is a semisimple R -module.

To prove this, we'll use the following lemma.

LEMMA 14.5

Let R be a ring.

- (1) If $\{M_{\alpha}\}_{\alpha \in X}$ is a family of left R -modules where each M_{α} is semisimple, then $\bigoplus_{\alpha \in X} M_{\alpha}$ is semisimple.
- (2) If M is a semisimple left R -module and $L \subseteq M$ is a submodule of M , then M/L is also semisimple.

First, we'll show that Theorem 14.4 easily follows from Lemma 14.5.

PROOF OF THEOREM 14.4. (\Rightarrow) If every left R -module is semisimple, then certainly ${}_R R$ is semisimple.

(\Leftarrow) Let M be a left R -module. We saw in Proposition 13.5 that $M \cong R^{\oplus X}/L$ where $L \subseteq \bigoplus_{x \in X} R$. If ${}_R R$ is semisimple, then

$$\bigoplus_{x \in X} {}_R R = \bigoplus_{x \in X} R$$

is semisimple by taking $M_{\alpha} = {}_R R$ for each $\alpha \in X$ and applying (1) of Lemma 14.5. It follows from (2) that $M \cong \bigoplus_{x \in X} R/L$ is semisimple. \square

Now, it only remains to prove Lemma 14.5.

PROOF OF LEMMA 14.5.

- (1) Write each M_{α} as a direct sum of simple R -modules

$$M_{\alpha} = \bigoplus_{\beta \in X_{\alpha}} V_{\alpha, \beta}.$$

It follows that

$$\bigoplus_{\alpha \in X} M_\alpha = \bigoplus_{\alpha \in X} \bigoplus_{\beta \in X_\alpha} V_{\alpha, \beta} = \bigoplus_{(\alpha, \beta) : \alpha \in X, \beta \in X_\alpha} V_{\alpha, \beta}$$

is the direct sum of simple modules, so it is semisimple.

(2) Since M is semisimple, we can write

$$M = \bigoplus_{\alpha \in X} V_\alpha,$$

where each V_α is simple. Let $\pi : M \rightarrow M/L$ be the canonical projection. Consider $\pi(V_\alpha) \subseteq M/L$. We claim that either $\pi(V_\alpha) \cong V_\alpha$ or $\pi(V_\alpha) = (0)$. First, we restrict π to V_α to obtain the map

$$\pi|_{V_\alpha} : V_\alpha \rightarrow \pi(V_\alpha),$$

which is a surjective R -module homomorphism. Since $\ker(\pi|_{V_\alpha})$ is a submodule of V_α , we either have $\ker(\pi|_{V_\alpha}) = (0)$ or $\ker(\pi|_{V_\alpha}) = V_\alpha$ by the simplicity of V_α . In the first case, $\pi|_{V_\alpha}$ is a bijection, so $\pi(V_\alpha) \cong V_\alpha$. In the second case, we obtain $\pi(V_\alpha) = (0)$.

Let $Y = \{\alpha \in X : \pi(V_\alpha) \cong V_\alpha\} \subseteq X$. We claim that

$$M/L = \sum_{\alpha \in Y} \pi(V_\alpha).$$

Since $\pi : M \rightarrow M/L$ is onto and $M = \sum_{\alpha \in X} V_\alpha$, we have

$$M/L = \pi(M) = \pi\left(\sum_{\alpha \in X} V_\alpha\right) = \sum_{\alpha \in X} \pi(V_\alpha) = \sum_{\alpha \in Y} \pi(V_\alpha),$$

where the last equality is because $\pi(V_\alpha) = (0)$ for all $\alpha \in X \setminus Y$, which contributes nothing to the sum.

Note that the above sum is not necessarily a direct sum. This is where we'll use Zorn's lemma to show that it is isomorphic to a direct sum of simples. Let

$$\mathcal{S} = \left\{ Z \subseteq Y : \sum_{\alpha \in Z} \pi(V_\alpha) \text{ is a direct sum} \right\}.$$

First, we note that $\mathcal{S} \neq \emptyset$ since empty sums are by definition direct sums, so $\emptyset \in \mathcal{S}$. Let $\{Z_\gamma\}_{\gamma \in \Gamma}$ be a chain in \mathcal{S} ordered by inclusion, where Γ is a totally ordered set. We must show that

$$Z := \bigcup_{\gamma \in \Gamma} Z_\gamma \in \mathcal{S},$$

which will be an upper bound in the chain, in which case we can apply Zorn's lemma to \mathcal{S} . So suppose towards a contradiction that $Z \notin \mathcal{S}$. Then the sum $\sum_{\alpha \in Z} \pi(V_\alpha)$ is not a direct sum. Therefore, there is a finite set of elements $\alpha_1, \dots, \alpha_s \in Z$ such that

$$\pi(V_{\alpha_1}) + \dots + \pi(V_{\alpha_s})$$

is not direct. There exists some $\gamma \in \Gamma$ such that $\alpha_1, \dots, \alpha_s \in Z_\gamma$, which would imply that $\sum_{\alpha \in Z_\gamma} \pi(V_\alpha)$ is not a direct sum, a contradiction. Therefore, $Z \in \mathcal{S}$, and by Zorn's lemma, there exists a maximal element $Y_0 \in \mathcal{S}$ with $Y_0 \subseteq Y$.

Finally, we'll show that $N = \sum_{\alpha \in Y_0} \pi(V_\alpha)$ is direct and equal to M/L . The fact that it is direct is immediate since $Y_0 \in \mathcal{S}$. Recall that

$$M/L = \sum_{\alpha \in Y} \pi(V_\alpha).$$

If $\pi(V_\alpha) \subseteq N$ for all $\alpha \in Y$, we have $\sum_{\alpha \in Y} \pi(V_\alpha) \subseteq N$. This gives $M/L \subseteq N$, and hence $N = M/L$. Therefore, it is enough to show that $\pi(V_\alpha) \subseteq N$ for any $\alpha \in Y$. Suppose that this was not the case, so $\pi(V_{\alpha_0}) \not\subseteq N$ for some $\alpha_0 \in Y$. We will show that

$$\pi(V_{\alpha_0}) + \bigoplus_{\alpha \in Y_0} \pi(V_\alpha)$$

is a direct sum, which will give a contradiction as $\{\alpha_0\} \cup Y_0 \in \mathcal{S}$ contradicts the maximality of Y_0 in \mathcal{S} . Note that $\pi(V_{\alpha_0})$ is simple. If $\pi(V_{\alpha_0}) = (0)$, then $\pi(V_{\alpha_0}) + \bigoplus_{\alpha \in Y_0} \pi(V_\alpha)$ is a direct sum. Otherwise, $\pi(V_{\alpha_0})$ is already in $\bigoplus_{\alpha \in Y_0} \pi(V_\alpha)$, which means that $\pi(V_{\alpha_0}) \subseteq N$, a contradiction. \square

15 Uniqueness of decompositions, characters (10/18/2021)

We were looking at rings of the form

$$R \cong M_{n_1}(k) \times \cdots \times M_{n_s}(k).$$

So far, we have shown the following facts.

- Up to isomorphism of R -modules, R has exactly s simple left R -modules V_1, \dots, V_s .
- We have the decomposition ${}_R R \cong V_1^{n_1} \oplus \cdots \oplus V_s^{n_s}$.
- The ring R is semisimple; that is, every R -module can be written as the direct sum of simple submodules.

Observe that we have (2) of Theorem 12.4, because we already know that

$$k[G] \cong M_{n_1}(k) \times \cdots \times M_{n_s}(k)$$

where s is the number of conjugacy classes of G so that $k[G]$ is a semisimple ring. It only remains to prove (3), the uniqueness part. That is, if $V_1^{a_1} \oplus \cdots \oplus V_s^{a_s} \cong V_1^{b_1} \oplus \cdots \oplus V_s^{b_s}$ is an R -module isomorphism, then $a_i = b_i$ for all $i = 1, \dots, s$. First, we will make a remark.

REMARK 15.1

If R is a k -algebra and M and N are left R -modules, then $\text{Hom}_R(M, N)$ is a k -vector space. Indeed, for a homomorphism $\Phi : M \rightarrow N$ and $\lambda \in k$, we can define scalar multiplication by

$$(\lambda \cdot \Phi)(m) := \lambda \cdot \Phi(m).$$

Note that this only works because k is central; in the general case where R is not a k -algebra, we can only say that $\text{Hom}_R(M, N)$ is an abelian group.

PROOF OF UNIQUENESS. Suppose that

$$f : V_1^{a_1} \oplus \cdots \oplus V_s^{a_s} \rightarrow V_1^{b_1} \oplus \cdots \oplus V_s^{b_s}$$

is an R -module isomorphism. Then for each $i = 1, \dots, s$, we have

$$\text{Hom}_R(V_1^{a_1} \oplus \cdots \oplus V_s^{a_s}, V_i) \cong \text{Hom}_R(V_1^{b_1} \oplus \cdots \oplus V_s^{b_s}, V_i)$$

as k -vector spaces. Looking at the left-hand side, we have

$$\text{Hom}_R(V_1^{a_1} \oplus \cdots \oplus V_s^{a_s}, V_i) \cong \prod_{j=1}^s \text{Hom}_R(V_j, V_i) \cong \text{Hom}_R(V_i, V_i)^{a_i} \cong k^{a_i},$$

where the first isomorphism is due to (1) of Remark 13.2, and the second isomorphism is because

$$\mathrm{Hom}_R(V_j, V_i) = \begin{cases} (0) & \text{if } j \neq i, \\ k & \text{if } j = i. \end{cases}$$

Similarly, we find that

$$\mathrm{Hom}_R(V_1^{b_1} \oplus \cdots \oplus V_s^{b_s}, V_i) \cong k^{b_i}.$$

This gives $k^{a_i} \cong k^{b_i}$, and hence $a_i = b_i$ for all $i = 1, \dots, s$. \square

Now, we're ready to move on to character theory. Recall that in our usual setting, we have a finite group G and an algebraically closed field k such that $\mathrm{char}(k) \nmid |G|$. Let V be a finite-dimensional $k[G]$ -module. Then $k[G]$ has s pairwise non-isomorphic $k[G]$ -modules V_1, \dots, V_s , where s is the number of conjugacy classes of G . Then V gives us a group homomorphism

$$\rho_V : G \rightarrow \mathrm{GL}(V) \cong \mathrm{GL}_n(k)$$

where $n = \dim_k(V)$, with the rule

$$\rho_V(g)(v) := g \cdot v.$$

Recall that linear maps $T : V \rightarrow V$ have a trace $\mathrm{Tr}(T)$.

REMARK 15.2

If $\{v_1, \dots, v_n\}$ is a basis for V , then we can write

$$Tv_j = \sum_{i=1}^n a_{ij}v_i, \quad \mathrm{Tr}(T) = \sum_{i=1}^n a_{ii}.$$

DEFINITION 15.3

We define the **character** of V as the map $\chi_V : G \rightarrow k$ given the rule

$$\chi_V(g) := \mathrm{Tr}(\rho_V(g)).$$

EXAMPLE 15.4

Let $G = S_3$, and let $V = \mathbb{C}e_1 \oplus \mathbb{C}e_2 \oplus \mathbb{C}e_3$, which is a 3-dimensional vector space. We can give V a structure as a $\mathbb{C}[S_3]$ -module by the action

$$\sigma \cdot e_j = e_{\sigma(j)},$$

and hence

$$\sigma(\alpha e_1 + \beta e_2 + \gamma e_3) = \alpha e_{\sigma(1)} + \beta e_{\sigma(2)} + \gamma e_{\sigma(3)}.$$

In particular, we are taking the usual action of S_3 on $\{1, 2, 3\}$, and we're extending it to a vector space. Now, we'll determine the representation $\rho_V : G \rightarrow \mathrm{GL}_3(\mathbb{C}) \cong \mathrm{GL}(V)$. We have

$$\begin{aligned} \rho_V(\mathrm{id}) &= \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}, & \rho_V((12)) &= \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}, & \rho_V((13)) &= \begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{pmatrix}, \\ \rho_V((23)) &= \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}, & \rho_V((123)) &= \begin{pmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix}, & \rho_V((132)) &= \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{pmatrix}. \end{aligned}$$

Now, we can take a look at the character $\chi_V : G \rightarrow \mathbb{C}$; we see that

$$\begin{array}{lll} \chi_V(\text{id}) = 3, & \chi_V((12)) = 1, & \chi_V((13)) = 1, \\ \chi_V((23)) = 1, & \chi_V((123)) = 0, & \chi_V((132)) = 0. \end{array}$$

Observe that $\chi_V(\sigma)$ gives us the number of fixed points of $\sigma \in S_3$. Moreover, if $\chi_V(\sigma) = \chi_V(\tau)$, then σ and τ are in the same conjugacy class.

Recall that $f : G \rightarrow k$ is a class function if it is constant when restricted to conjugacy classes; that is, $f(xgx^{-1}) = f(g)$ for all $g, x \in G$.

THEOREM 15.5

Let V be a finite-dimensional $k[G]$ -module. Then $\chi_V : G \rightarrow k$ is a class function.

PROOF. Since $\rho_V : G \rightarrow \text{GL}(V)$ is a group homomorphism, we have

$$\rho_V(xgx^{-1}) = \rho_V(x)\rho_V(g)\rho_V(x)^{-1}.$$

It follows that

$$\text{Tr}(\rho_V(xgx^{-1})) = \text{Tr}(\rho_V(x)\rho_V(g)\rho_V(x)^{-1}) = \text{Tr}(\rho_V(g)),$$

where the last equality is because similar matrices preserve trace. In particular, we have $\chi_V(xgx^{-1}) = \chi_V(g)$ for all $g, x \in G$, so χ_V is a class function. \square

REMARK 15.6

- (1) If $V \cong W$ as $k[G]$ -modules, then $\chi_V = \chi_W$. (In fact, in the case that V and W are finite-dimensional, the converse is also true.)
- (2) If W_1 and W_2 are $k[G]$ -modules, then $\chi_{W_1 \oplus W_2} = \chi_{W_1} + \chi_{W_2}$. By induction, we also see that if W_1, \dots, W_r are $k[G]$ -modules, then

$$\chi_{W_1 \oplus \dots \oplus W_r} = \sum_{i=1}^r \chi_{W_i}.$$

PROOF.

- (1) Let $f : V \rightarrow W$ be a $k[G]$ -module isomorphism. Let $\{v_1, \dots, v_n\}$ be a basis for V as a k -vector space. Then

$$\chi_V(g) = \text{Tr}(a_{ij}) = a_{11} + a_{22} + \dots + a_{nn},$$

where $g \cdot v_j = \sum_{i=1}^n a_{ij} v_i$. Notice that $\{f(v_1), \dots, f(v_n)\}$ is a basis for W as a k -vector space, and f is $k[G]$ -linear, so

$$g \cdot f(v_j) = f(g \cdot v_j) = f\left(\sum_{i=1}^n a_{ij} v_i\right) = \sum_{i=1}^n a_{ij} f(v_i).$$

Now, we see that $\chi_W(g) = \text{Tr}(a_{ij}) = a_{11} + \dots + a_{nn} = \chi_V(g)$.

- (2) Write $W = W_1 \oplus W_2$. Let $\{v_1, \dots, v_m\}$ be a basis for W_1 , and let $\{v_{m+1}, \dots, v_n\}$ be a basis for W_2 . Observe that

$$\rho_W(g)(v_i) = \begin{cases} \rho_{W_1}(g)(v_i) & \text{if } i = 1, \dots, m, \\ \rho_{W_2}(g)(v_i) & \text{if } i = m+1, \dots, n. \end{cases}$$

Then with respect to the basis $\{v_1, \dots, v_n\}$, we have

$$\rho_W(g) = \left(\begin{array}{c|c} \rho_{W_1}(g) & 0 \\ \hline 0 & \rho_{W_2}(g) \end{array} \right).$$

In particular, we find that $\chi_W(g) = \chi_{W_1}(g) + \chi_{W_2}(g)$. \square

These results are important to us because if V is a finite-dimensional $k[G]$ -module, then V decomposes as

$$V \cong V_1^{a_1} \oplus \dots \oplus V_s^{a_s},$$

where each $a_i \geq 0$, V_1, \dots, V_s are simple modules, and s is the number of conjugacy classes of G . Then

$$\chi_V = a_1\chi_{V_1} + a_2\chi_{V_2} + \dots + a_s\chi_{V_s}.$$

Moreover, if $V = {}_{k[G]}k[G]$, then we have seen that

$$V \cong V_1^{n_1} \oplus \dots \oplus V_s^{n_s},$$

where $k[G] \cong M_{n_1}(k) \times \dots \times M_{n_s}(k)$. Recall that

$$\chi_V(g) = \begin{cases} |G| & \text{if } g = 1, \\ 0 & \text{if } g \neq 1, \end{cases}$$

which gives us the nice fact that if $k[G] \cong M_{n_1}(k) \times \dots \times M_{n_s}(k)$, then

$$\left(\sum_{i=1}^s n_i \chi_{V_i} \right)(g) = \sum_{i=1}^s n_i \chi_{V_i}(g) = \begin{cases} |G| & \text{if } g = 1, \\ 0 & \text{if } g \neq 1. \end{cases}$$

16 Character tables, an “inner product” of maps (10/20/2021)

Let G be a finite group, and let k be an algebraically closed field with $\text{char}(k) \nmid |G|$. Then

$$k[G] \cong \prod_{i=1}^s M_{n_i}(k)$$

as k -algebras, where s is the number of conjugacy classes of G , and $\sum_{i=1}^s n_i^2 = |G|$. Moreover, $k[G]$ has s pairwise non-isomorphic simple modules (or irreducible representations) V_1, \dots, V_s , with $V_i \cong k^{n_i \times 1}$.

Moreover, every left $k[G]$ -module V decomposes as

$$V \cong V_1^{a_1} \oplus \dots \oplus V_s^{a_s},$$

and this decomposition is unique. We also have a representation

$$\rho_V : G \rightarrow \text{GL}(V),$$

which gives rise to the character $\chi_V : G \rightarrow k$ of V , with the formula

$$\chi_V = \sum_{i=1}^s a_i \chi_{V_i}.$$

Notice that $\chi_V(1) = \text{Tr}(\rho_V(1)) = \text{Tr}(I_n) = n = \dim_k(V)$, so by taking the module $L = {}_{k[G]}k[G]$, we have

$$\chi_L = \sum_{i=1}^s n_i \chi_{V_i},$$

and for $g \in G$, we saw in the previous lecture that

$$\chi_L(g) = \begin{cases} |G| & \text{if } g = 1, \\ 0 & \text{if } g \neq 1. \end{cases}$$

What are the irreducible representations of a finite abelian group G ? Assume that $|G| = n$, and k is an algebraically closed field with $\text{char}(k) \nmid n$. We see that $k[G] \cong k^n$, which implies that there are n inequivalent irreducible representations. Now, since G is abelian, we can write

$$G \cong C_{d_1} \times C_{d_2} \times \cdots \times C_{d_r},$$

where C_j denotes the cyclic group of order j . We can think of this as

$$G \cong \langle x_1 \mid x_1^{d_1} = 1 \rangle \times \cdots \times \langle x_r \mid x_r^{d_r} = 1 \rangle.$$

We know all simple $k[G]$ -modules are one-dimensional as k -vector spaces. In particular, if V is simple, then

$$\rho_V : G \rightarrow \text{GL}_1(k) \cong k^* = k \setminus \{0\}.$$

This means that if $\rho_V(x_i) = \omega_i \in k^*$, then

$$1 = \rho_V(1) = \rho_V(x_i^{d_i}) = \omega_i^{d_i}.$$

That is, each ω_i is a d_i -th root of unity, so there are $d_1 \cdots d_r = |G|$ choices for ρ_V . On the other hand, we already know that there are $d_1 \cdots d_r$ pairwise inequivalent irreducible representations, so these are in fact all of them. In this case, notice that $\chi_V = \rho_V$.

EXAMPLE 16.1

Suppose that $G_1 = C_2 \times C_2 = \langle x \mid x^2 = 1 \rangle \times \langle y \mid y^2 = 1 \rangle$ and $G_2 = C_4 = \langle z \mid z^4 = 1 \rangle$. We compute the character tables of G_1 and G_2 ; namely, the characters of the representations.

G_1	1	x	y	xy
χ_1	1	1	1	1
χ_2	1	1	-1	-1
χ_3	1	-1	1	-1
χ_4	1	-1	-1	1

G_2	1	z	z^2	z^3
χ_1	1	1	1	1
χ_2	1	i	-1	$-i$
χ_3	1	-1	1	-1
χ_4	1	$-i$	-1	i

EXAMPLE 16.2

Let $G = S_3$ and $k = \mathbb{C}$. We recall that $\mathbb{C}[S_3] \cong \mathbb{C} \times \mathbb{C} \times M_2(\mathbb{C})$. Then S_3 has three pairwise inequivalent irreducible representations, and these have dimensions 1, 1, and 2 respectively. Moreover, recall that for a finite-dimensional $k[G]$ -module V , its character $\chi_V : G \rightarrow k$ is a class function. Therefore, to compute the character table of S_3 , it suffices to consider the values of the characters on each conjugacy class.

First, the identity element is always sent to the dimension of the representation, so we obtain $\chi_1(\text{id}) = \chi_2(\text{id}) = 1$ and $\chi_3(\text{id}) = 2$. Since $(12)^2 = \text{id}$, we have $\chi_i((12))^2 = \chi_i(\text{id}) = 1$ for $i \in \{1, 2\}$, yielding $\chi_1((12)) = 1$ and $\chi_2((12)) = -1$.

Next, recall from Assignment 3 Question 1 that the one-dimensional irreducible representations come from G/G' . More precisely, if V is a simple one-dimensional $k[G]$ -module, then we obtain the following commutative diagram, where we note that k^* is an abelian group.

$$\begin{array}{ccc}
 G & \xrightarrow{\rho_V} & \mathrm{GL}(V) \cong k^* \\
 \pi \downarrow & \nearrow \tilde{\rho}_V & \\
 G/G' & &
 \end{array}$$

In our case, we have $S'_3 = A_3$ and $S_3/A_3 = C_2$, which gives us the following diagram.

$$\begin{array}{ccc}
 G & \xrightarrow{\rho_V} & \mathrm{GL}(V) \cong k^* \\
 \pi \downarrow & \nearrow \tilde{\rho}_V & \\
 C_2 & &
 \end{array}$$

In particular, everything in A_3 has to be in the kernel and gets sent to 1, so $\chi_1((123)) = \chi_2((123)) = 1$. The last row is more difficult to find directly. However, if we know everything in the character table except for the last row, then there's an easy way to compute it. Let

$$\chi_L = \chi_1 + \chi_2 + 2\chi_3.$$

We recall that $\chi_L(\sigma) = 0$ for all $\sigma \neq \mathrm{id}$; in particular, we have $\chi_L((12)) = \chi_L((123)) = 0$. This gives

$$\chi_1((12)) + \chi_2((12)) + 2\chi_3((12)) = 0,$$

and rearranging this, we obtain

$$\chi_3((12)) = -\frac{1}{2}(\chi_1((12)) + \chi_2((12))) = -\frac{1}{2}(1 + (-1)) = 0.$$

Similarly, we find that $\chi_3((123)) = -1$, so we have now completed the character table of S_3 .

S_3	[id]	[(12)]	[(123)]
χ_1	1	1	1
χ_2	1	-1	1
χ_3	2	0	-1

REMARK 16.3

Notice that for the $\mathbb{C}[S_3]$ -module $V = \mathbb{C}^{3 \times 1}$ given the permutation representation, $\chi_V(\sigma)$ gives the number of fixed points of $\sigma \in S_3$. Then we have $\chi_V(\mathrm{id}) = 3$, $\chi_V((12)) = 1$, and $\chi_V((123)) = 0$, so we find that $\chi_V = \chi_1 + \chi_3$ simply from the character table.

EXAMPLE 16.4

Let $G = Q_8 = \{\pm 1, \pm i, \pm j, \pm k\}$, where $ij = k$ and $i^2 = j^2 = k^2 = -1$. Recall that

$$\mathbb{C}[Q_8] \cong \mathbb{C}^4 \times M_2(\mathbb{C}),$$

so Q_8 has five conjugacy classes; they are $\{1\}$, $\{-1\}$, $\{i, -i\}$, $\{j, -j\}$, and $\{k, -k\}$. Observe that

$Q'_8 = \{\pm 1\}$, which implies that

$$Q_8/Q'_8 = \langle i, j \mid i^2 = j^2 = 1, ij = ji \rangle \cong C_2 \times C_2.$$

Now, the first four rows of the character table are easy to compute, as well as the first column.

Q_8	$[1]$	$[-1]$	$[i]$	$[j]$	$[k] = [ij]$
χ_1	1	1	1	1	1
χ_2	1	1	1	-1	-1
χ_3	1	1	-1	1	-1
χ_4	1	1	-1	-1	1
χ_5	2				

To obtain the last row, we apply the same trick as the previous example; we set

$$\chi_L = \chi_1 + \chi_2 + \chi_3 + \chi_4 + 2\chi_5$$

and use the fact that $\chi_L(g) = 0$ when $g \neq 1$. This will finish the character table.

Q_8	$[1]$	$[-1]$	$[i]$	$[j]$	$[k] = [ij]$
χ_1	1	1	1	1	1
χ_2	1	1	1	-1	-1
χ_3	1	1	-1	1	-1
χ_4	1	1	-1	-1	1
χ_5	2	-2	0	0	0

We will soon see the interesting fact that if G is a group and $\Phi, \Psi : G \rightarrow \mathbb{C}$ are maps, then we can define an “inner product” by

$$\langle \Phi, \Psi \rangle_G = \frac{1}{|G|} \sum_{g \in G} \Phi(g) \Psi(g^{-1}).$$

Note that this is not actually an inner product, as it fails to satisfy some properties. However, we see that it is \mathbb{C} -bilinear; indeed, for $\lambda \in \mathbb{C}$, we have

$$\langle \Phi_1 + \lambda \Phi_2, \Psi \rangle_G = \frac{1}{|G|} \sum_{g \in G} (\Phi_1(g) + \lambda \Phi_2(g)) \Psi(g^{-1}) = \langle \Phi_1, \Psi \rangle_G + \lambda \langle \Phi_2, \Psi \rangle_G,$$

and the other direction can be checked similarly. Moreover, $\langle \cdot, \cdot \rangle_G$ is symmetric, since

$$\langle \Phi, \Psi \rangle_G = \frac{1}{|G|} \sum_{g \in G} \Phi(g) \Psi(g^{-1}) = \frac{1}{|G|} \sum_{x \in G} \Phi(x^{-1}) \Psi(x) = \langle \Psi, \Phi \rangle_G,$$

where in the second equality, we used the substitution $x = g^{-1}$.

In the following lectures, we’ll see that characters are orthonormal with respect to this “inner product”.

17 Orthogonality of characters over “inner product” (10/22/2021)

For this part of the course, we’ll be working over \mathbb{C} . Last time, for a pair of maps $\Phi, \Psi : G \rightarrow \mathbb{C}$, we defined the “inner product”

$$\langle \Phi, \Psi \rangle_G = \frac{1}{|G|} \sum_{g \in G} \Phi(g) \Psi(g^{-1}),$$

and saw that this was \mathbb{C} -bilinear and symmetric. We now make an important remark towards showing that $\langle \cdot, \cdot \rangle_G$ is a true inner product when working with characters.

REMARK 17.1

If χ is a character, then $\chi(g^{-1}) = \overline{\chi(g)}$.

PROOF. We have $\chi(g) = \text{Tr}(\rho(g))$ where $\rho : G \rightarrow \text{GL}_n(\mathbb{C})$ is a representation. Let $g \in G$. Notice that $\rho(g)$ is triangularizable, so

$$S^{-1}\rho(g)S = \begin{pmatrix} \lambda_1 & & * \\ & \ddots & \\ 0 & & \lambda_n \end{pmatrix},$$

where $\lambda_1, \dots, \lambda_n$ are the eigenvalues of $\rho(g)$. Since G is finite, there exists an integer $d \geq 1$ such that $g^d = 1$. Then, we can write

$$\rho(g)^d = \rho(g^d) = \rho(1) = I,$$

which implies that

$$(S^{-1}\rho(g)S)^d = (S^{-1}\rho(g)S)(S^{-1}\rho(g)S) \cdots (S^{-1}\rho(g)S) = S^{-1}\rho(g)^d S = S^{-1}IS = I.$$

Therefore, we find that

$$\begin{pmatrix} \lambda_1^d & & * \\ & \ddots & \\ 0 & & \lambda_n^d \end{pmatrix} = I.$$

In particular, $\lambda_1, \dots, \lambda_n$ are d -th roots of unity. Since $\rho(g^{-1})$ is the inverse of $\rho(g)$, we have

$$\rho(g^{-1}) = \begin{pmatrix} \lambda_1^{-1} & & * \\ & \ddots & \\ 0 & & \lambda_n^{-1} \end{pmatrix}.$$

Finally, it follows that

$$\chi(g^{-1}) = \text{Tr}(\rho(g^{-1})) = \lambda_1^{-1} + \cdots + \lambda_n^{-1} = \overline{\lambda_1} + \cdots + \overline{\lambda_n} = \overline{\chi(g)}. \quad \square$$

Let $\mathcal{C}_1, \dots, \mathcal{C}_s$ be the conjugacy classes of G , and let g_i be a representative of \mathcal{C}_i for each $i = 1, \dots, s$. If χ_1 and χ_2 are characters, then

$$\begin{aligned} \langle \chi_1, \chi_2 \rangle_G &= \frac{1}{|G|} \sum_{g \in G} \chi_1(g) \chi_2(g^{-1}) \\ &= \frac{1}{|G|} \sum_{g \in G} \chi_1(g) \overline{\chi_2(g)} \\ &= \frac{1}{|G|} \sum_{i=1}^s \sum_{h \in \mathcal{C}_i} \chi_1(h) \overline{\chi_2(h)} \\ &= \frac{1}{|G|} \sum_{i=1}^s |\mathcal{C}_i| \chi_1(g_i) \overline{\chi_2(g_i)}, \end{aligned}$$

where the last equality follows since χ_1 and χ_2 are class functions.

We'll now show that if V_1, \dots, V_s are the inequivalent irreducible representations of G with $\chi_i = \chi_{V_i}$, then $\langle \chi_i, \chi_j \rangle_G = \delta_{ij}$, where δ_{ij} denotes the Kronecker delta.

First, we will consider an averaging trick. Let G be a finite group, and let k be an algebraically closed field such that $\text{char}(k) \nmid |G|$. Let V and W be $k[G]$ -modules. If $T : V \rightarrow W$ is a k -linear transformation, we can define a map $\hat{T} : V \rightarrow W$ where for $v \in V$, we have

$$\hat{T}(v) = \frac{1}{|G|} \sum_{g \in G} g \cdot T(g^{-1} \cdot v).$$

This makes sense because $T(g^{-1} \cdot v) \in W$.

THEOREM 17.2

If $T : V \rightarrow W$ is k -linear, then $\hat{T} : V \rightarrow W$ as above is $k[G]$ -linear.

PROOF. It suffices to show that $\hat{T}(h \cdot v) = h \cdot \hat{T}(v)$ for all $h, v \in V$, because every element in $k[G]$ is a linear combination of elements in G . By a direct computation, we have

$$\begin{aligned} \hat{T}(h \cdot v) &= \frac{1}{|G|} \sum_{g \in G} g \cdot T(g^{-1} \cdot (h \cdot v)) \\ &= \frac{1}{|G|} \sum_{g \in G} g \cdot T((g^{-1} \cdot h) \cdot v) \\ &= \frac{1}{|G|} \sum_{x \in G} h \cdot x \cdot T(x^{-1} \cdot v) \quad (\text{substitute } x = h^{-1}g) \\ &= h \cdot \frac{1}{|G|} \sum_{x \in G} x \cdot T(x^{-1} \cdot v) = h \cdot \hat{T}(v). \end{aligned} \quad \square$$

We now return to working over \mathbb{C} , and look at some consequences of the previous result.

If V and W are non-isomorphic simple $\mathbb{C}[G]$ -modules and $T : V \rightarrow W$ is \mathbb{C} -linear, then $\hat{T} \equiv 0$ since $\text{Hom}_{\mathbb{C}[G]}(V, W) = (0)$. On the other hand, recall that

$$\text{Hom}_{\mathbb{C}[G]}(V, V) = \text{End}_{\mathbb{C}[G]}(V) = \mathbb{C}$$

by Schur's lemma. This implies that if $T : V \rightarrow V$ is \mathbb{C} -linear, then $\hat{T} : V \rightarrow V$ is just scalar multiplication by some $\lambda \in \mathbb{C}$. That is, for all $v \in V$, we have

$$\hat{T}(v) = \lambda v.$$

We now determine what λ is. Let $L_g : V \rightarrow V$ be the map given by $L_g(v) = g \cdot v$. Then

$$\begin{aligned} \text{Tr}(\hat{T}) &= \text{Tr} \left(\frac{1}{|G|} \sum_{g \in G} L_g \circ T \circ L_g^{-1} \right) \\ &= \frac{1}{|G|} \sum_{g \in G} \text{Tr}(L_g \circ T \circ L_g^{-1}) \\ &= \frac{1}{|G|} \sum_{g \in G} \text{Tr}(T) = \text{Tr}(T). \end{aligned}$$

On the other hand, we already know that $\text{Tr}(\hat{T}) = \lambda \cdot \dim V$, so

$$\lambda = \frac{\text{Tr}(T)}{\dim V}.$$

Let V and W be two simple non-isomorphic $\mathbb{C}[G]$ -modules with bases $\{v_1, \dots, v_m\}$ and $\{w_1, \dots, w_n\}$ respectively. Then, we obtain representations

$$\begin{aligned}\rho_1 : G &\rightarrow \mathrm{GL}_m(\mathbb{C}) \cong \mathrm{GL}(V), \\ \rho_2 : G &\rightarrow \mathrm{GL}_n(\mathbb{C}) \cong \mathrm{GL}(W).\end{aligned}$$

Note that if we want to find the matrix of a linear transformation, we pick our basis, and to get the j -th column, we apply the transformation to the j -th element of our basis. In particular, we find that

$$\rho_1(g) \cdot v_j = \sum_{i=1}^m \rho_1(g)_{ij} \cdot v_i, \quad \rho_2(g) \cdot w_j = \sum_{i=1}^n \rho_2(g)_{ij} \cdot w_i.$$

Notice that we can view $\rho_1(g) = (\rho_1(g))_{ij}$ and $\rho_2(g) = (\rho_2(g))_{ij}$ as functions from G to \mathbb{C} by looking at their (i, j) -th entries.

THEOREM 17.3

For all $1 \leq i, j \leq m$ and $1 \leq p, q \leq n$, we have $\langle (\rho_1)_{ij}, (\rho_2)_{pq} \rangle_G = 0$.

PROOF. Fix some $1 \leq i \leq m$ and $1 \leq q \leq n$. Define a linear transformation $T : V \rightarrow W$ by $T(v_i) = w_q$, and $T(v_k) = 0$ whenever $k \neq i$. Then $\hat{T} \equiv 0$ since V and W are non-isomorphic simple modules. For all $1 \leq j \leq m$, we have

$$0 = \hat{T}(v_j) = \frac{1}{|G|} \sum_{g \in G} g \cdot T(g^{-1} \cdot v_j) = \frac{1}{|G|} \sum_{g \in G} \rho_2(g) \cdot T(\rho_1(g^{-1}) \cdot v_j).$$

By definition, we have

$$\rho_1(g^{-1}) \cdot v_j = \sum_{k=1}^m \rho_1(g^{-1})_{kj} \cdot v_k,$$

which gives us

$$T(\rho_1(g^{-1}) \cdot v_j) = T\left(\sum_{k=1}^m \rho_1(g^{-1})_{kj} \cdot v_k\right) = \rho_1(g^{-1})_{ij} \cdot T(v_i) = \rho_1(g^{-1})_{ij} \cdot w_q,$$

where the second equality comes from throwing everything away except when $k = i$. Finally, we obtain

$$\begin{aligned}0 &= \frac{1}{|G|} \sum_{g \in G} \rho_2(g) \cdot T(\rho_1(g^{-1}) \cdot v_j) \\ &= \frac{1}{|G|} \sum_{g \in G} \rho_1(g^{-1})_{ij} \cdot \rho_2(g) \cdot w_q \\ &= \frac{1}{|G|} \sum_{g \in G} \rho_1(g^{-1})_{ij} \left[\sum_{k=1}^n \rho_2(g)_{kq} \cdot w_k \right] \\ &= \frac{1}{|G|} \sum_{g \in G} \rho_1(g^{-1})_{ij} \cdot \rho_2(g)_{pq} \\ &= \langle (\rho_2)_{pq}, (\rho_1)_{ij} \rangle_G = \langle (\rho_1)_{ij}, (\rho_2)_{pq} \rangle_G.\end{aligned}$$

Since $1 \leq i, j \leq m$ and $1 \leq p, q \leq n$ were arbitrary, we are done. \square

Now, we can show that the characters are orthonormal.

COROLLARY 17.4

If V and W are non-isomorphic simple $\mathbb{C}[G]$ -modules, then $\langle \chi_V, \chi_W \rangle = 0$.

PROOF. Suppose that $\dim V = m$ and $\dim W = n$. Then we obtain representations

$$\begin{aligned}\rho_1 : G &\rightarrow \mathrm{GL}(V) \cong \mathrm{GL}_m(\mathbb{C}), \\ \rho_2 : G &\rightarrow \mathrm{GL}(W) \cong \mathrm{GL}_n(\mathbb{C}).\end{aligned}$$

We can write these in matrix form as

$$\begin{aligned}\rho_1(g) &= ((\rho_1)_{ij}(g))_{1 \leq i, j \leq m}, \\ \rho_2(g) &= ((\rho_2)_{ij}(g))_{1 \leq i, j \leq n}.\end{aligned}$$

By Theorem 17.3, we have $\langle (\rho_1)_{ij}, (\rho_2)_{pq} \rangle = 0$ for all $1 \leq i, j \leq m$ and $1 \leq p, q \leq n$. Notice that

$$\begin{aligned}\chi_V(g) &= \mathrm{Tr}(\rho_1(g)) = \sum_{i=1}^m (\rho_1)_{ii}(g), \\ \chi_W(g) &= \mathrm{Tr}(\rho_2(g)) = \sum_{j=1}^n (\rho_2)_{jj}(g),\end{aligned}$$

and it follows from the bilinearity of our “inner product” that

$$\langle \chi_V, \chi_W \rangle_G = \left\langle \sum_{i=1}^m (\rho_1)_{ii}, \sum_{j=1}^n (\rho_2)_{jj} \right\rangle_G = 0. \quad \square$$

18 Orthonormality of characters over “inner product” (10/25/2021)

Let $\mathcal{C}_1, \dots, \mathcal{C}_s$ be the conjugacy classes of G , and let g_1, \dots, g_s be representatives of the conjugacy classes. We showed that for characters χ and χ' , we have

$$\langle \chi, \chi' \rangle_G = \frac{1}{|G|} \sum_{i=1}^s |\mathcal{C}_i| \chi(g_i) \overline{\chi'(g_i)}.$$

Now, for general class functions $\Theta, \Omega : G \rightarrow \mathbb{C}$, we define

$$\langle \Theta, \Omega \rangle_G = \frac{1}{|G|} \sum_{i=1}^s |\mathcal{C}_i| \Theta(g_i) \overline{\Omega(g_i)}.$$

This definition turns the space of \mathbb{C} -valued class functions into a complex inner product space; we notice that

$$\langle \Theta, \Theta \rangle_G = \frac{1}{|G|} \sum_{i=1}^s |\mathcal{C}_i| |\Theta(g_i)|^2 \geq 0.$$

We'll show that if χ_1, \dots, χ_s are the inequivalent irreducible characters, then χ_1, \dots, χ_s forms an orthonormal basis for the \mathbb{C} -valued class functions.

First, we observe that given a class function $\Theta : G \rightarrow \mathbb{C}$, we have an element given by $(\Theta(g_1), \dots, \Theta(g_s)) \in \mathbb{C}^s$. In particular, this gives us a bijection between the \mathbb{C} -valued class functions and \mathbb{C}^s , since we can define a class function $\Theta : G \rightarrow \mathbb{C}$ by picking s values in \mathbb{C} and assigning them to the representatives g_1, \dots, g_s . Therefore, the space of \mathbb{C} -valued class functions is s -dimensional.

Notice that Corollary 17.4 already shows orthogonality. Let V be a simple $\mathbb{C}[G]$ -module with a representation

$$\rho : G \rightarrow \mathrm{GL}(V) \cong \mathrm{GL}_n(\mathbb{C}),$$

where V has basis $\{v_1, \dots, v_n\}$. Then we have $\rho(g) \cdot v_j = \sum_{i=1}^n \rho_{ij}(g) \cdot v_i$, where

$$\rho(g) = \begin{pmatrix} \rho_{11}(g) & \cdots & \rho_{1n}(g) \\ \vdots & \ddots & \vdots \\ \rho_{n1}(g) & \cdots & \rho_{nn}(g) \end{pmatrix}.$$

LEMMA 18.1

For all $1 \leq i, j, s, t \leq n$, we have

$$\langle \rho_{ij}, \rho_{st} \rangle_G = \frac{1}{\dim V} \delta_{it} \delta_{js} = \frac{1}{n} \delta_{it} \delta_{js},$$

where δ_{ij} denotes the Kronecker delta.

With the lemma, we can immediately prove orthonormality! Let $\chi = \mathrm{Tr}(\rho)$, so $\chi(g) = \rho_{11}(g) + \cdots + \rho_{nn}(g)$. Then we find that

$$\langle \chi, \chi \rangle_G = \langle \rho_{11} + \cdots + \rho_{nn}, \rho_{11} + \cdots + \rho_{nn} \rangle_G = \sum_{i=1}^n \sum_{j=1}^n \langle \rho_{ii}, \rho_{jj} \rangle_G.$$

Lemma 18.1 tells us that

$$\langle \rho_{ii}, \rho_{jj} \rangle_G = \begin{cases} 0 & \text{if } i \neq j, \\ 1/n & \text{if } i = j. \end{cases}$$

It follows that

$$\langle \chi, \chi \rangle_G = \sum_{i=1}^n \langle \rho_{ii}, \rho_{ii} \rangle_G = \sum_{i=1}^n \frac{1}{n} = 1.$$

Recall that if $T : V \rightarrow V$ is \mathbb{C} -linear, then we defined

$$\hat{T}(v) = \frac{1}{|G|} \sum_{g \in G} g \cdot T(g^{-1} \cdot v),$$

which we showed was $\mathbb{C}[G]$ -linear. Moreover, when V is simple, we showed that $\hat{T}(v) = \lambda v$, where $\lambda = \mathrm{Tr}(T)/\dim V$. We now prove Lemma 18.1.

PROOF OF LEMMA 18.1. Fix a basis $\{v_1, \dots, v_n\}$ for V . By definition, we know that

$$\rho(g) \cdot v_j = \sum_{i=1}^n \rho_{ij}(g) \cdot v_i,$$

where $\rho(g)$ denotes the linear transformation, and $\rho_{ij}(g) \in \mathbb{C}$ is an entry of the matrix. Let $T : V \rightarrow V$ be the \mathbb{C} -linear transformation defined by

$$T(v_k) = \begin{cases} v_t & \text{if } k = i, \\ 0 & \text{if } k \neq i. \end{cases}$$

Note that $\mathrm{Tr}(T) = \delta_{it}$, which means that

$$\hat{T}(v) = \frac{\delta_{it}}{n}$$

for all $v \in V$, where $n = \dim V$. In particular, notice that

$$\frac{\delta_{it}}{n} \cdot v_j = \hat{T}(v_j) = \frac{1}{|G|} \sum_{g \in G} \rho(g) \cdot T(\rho(g^{-1}) \cdot v_j). \quad (18.1)$$

We can write

$$T(\rho(g^{-1}) \cdot v_j) = T\left(\sum_{k=1}^n \rho(g^{-1})_{kj} \cdot v_k\right) = T(\rho(g^{-1})_{ij} \cdot v_i) = \rho(g^{-1})_{ij} \cdot v_t,$$

since we can throw out the terms where $k \neq i$. Following from equation (18.1), we get

$$\begin{aligned} \frac{\delta_{it}}{n} \cdot v_j &= \frac{1}{|G|} \sum_{g \in G} \rho(g) \cdot T(\rho(g^{-1}) \cdot v_j) \\ &= \frac{1}{|G|} \sum_{g \in G} \rho(g) \cdot (\rho(g^{-1})_{ij} \cdot v_t) \\ &= \frac{1}{|G|} \sum_{g \in G} \rho(g)_{ij}^{-1} \cdot (\rho(g) \cdot v_t) \\ &= \frac{1}{|G|} \sum_{g \in G} \rho(g)_{ij}^{-1} \left(\sum_{\ell=1}^n \rho(g)_{\ell t} \cdot v_\ell \right) \\ &= \sum_{\ell=1}^n \left(\frac{1}{|G|} \sum_{g \in G} \rho(g)_{ij}^{-1} \cdot \rho(g)_{\ell t} \right) \cdot v_\ell \\ &= \sum_{\ell=1}^n \langle \rho_{\ell t}, \rho_{ij} \rangle_G \cdot v_\ell. \end{aligned}$$

Now, we compare the coefficients. When $\ell \neq j$, the coefficient of v_ℓ on the left-hand side is 0, whereas it is $\langle \rho_{\ell t}, \rho_{ij} \rangle_G$ on the right-hand side. When $\ell = j$, the coefficients of v_ℓ are δ_{it}/n and $\langle \rho_{jt}, \rho_{ij} \rangle_G$ on the left-hand side and right-hand side, respectively. We conclude that

$$\langle \rho_{ij}, \rho_{\ell t} \rangle_G = \langle \rho_{\ell t}, \rho_{ij} \rangle_G = \delta_{\ell j} \cdot \frac{\delta_{it}}{n},$$

which completes the proof of the lemma. \square

THEOREM 18.2

If χ_1, \dots, χ_s are the inequivalent irreducible characters, then χ_1, \dots, χ_s forms an orthonormal basis for the space of \mathbb{C} -valued class functions.

PROOF. Notice that $\langle \chi_i, \chi_j \rangle_G = \delta_{ij}$ for all $1 \leq i, j \leq s$. Therefore, χ_1, \dots, χ_s are linearly independent as the space of \mathbb{C} -valued class functions is s -dimensional. Moreover, χ_1, \dots, χ_s spans, so they form an orthonormal basis. \square

What is the significance of this result? Recall that if V is a representation of G , then it can be decomposed as

$$V \cong V_1^{a_1} \oplus \dots \oplus V_s^{a_s},$$

where V_1, \dots, V_s are simples. Letting $\chi_i = \chi_{V_i}$, we have the formula

$$\chi_V = a_1 \chi_1 + \dots + a_s \chi_s.$$

In particular, notice that by orthonormality, we have

$$\langle \chi_V, \chi_i \rangle_G = \langle a_1 \chi_1 + \dots + a_s \chi_s, \chi_i \rangle_G = \langle a_i \chi_i, \chi_i \rangle_G = a_i \|\chi_i\|^2 = a_i.$$

19 Character tables of S_4 and S_5 (10/27/2021)

Recall that we can write $\mathbb{C}[G] \cong M_{n_1}(\mathbb{C}) \times \cdots \times M_{n_s}(\mathbb{C})$, where s is the number of conjugacy classes of G . Then, we obtain s irreducible characters χ_1, \dots, χ_s , with

$$\chi_i(1) = n_i,$$

where we call n_i the degree of χ_i for each $i = 1, \dots, s$. We also saw that

$$\delta_{ij} = \langle \chi_i, \chi_j \rangle_G = \frac{1}{|G|} \sum_{g \in G} \chi_i(g) \overline{\chi_j(g)}.$$

For a $\mathbb{C}[G]$ -module $V \cong V_1^{a_1} \oplus \cdots \oplus V_s^{a_s}$, we have the formula

$$\chi_V = a_1 \chi_1 + \cdots + a_s \chi_s,$$

where $\chi_i = \chi_{V_i}$ for all $i = 1, \dots, s$. We saw that this gives $a_i = \langle \chi_V, \chi_i \rangle_G$ by orthonormality. In particular, we find that

$$\langle \chi_V, \chi_V \rangle_G = \sum_{i=1}^s a_i^2 \|\chi_i\|^2 = \sum_{i=1}^s a_i^2.$$

Let's use our results to find the character tables of S_4 and S_5 .

EXAMPLE 19.1

To find the character table of S_4 , we first recall that $\mathbb{C}[S_4] \cong \mathbb{C} \times \mathbb{C} \times M_2(\mathbb{C}) \times M_3(\mathbb{C}) \times M_3(\mathbb{C})$, which we determined in Example 11.3. We also saw that the 5 conjugacy classes and their sizes were

$$\begin{aligned} \#[\text{id}] &= 1, \\ \#[(12)] &= 6, \\ \#[(123)] &= 8, \\ \#[(1234)] &= 6, \\ \#[(12)(34)] &= 3. \end{aligned}$$

Since $S'_4 = A_4$, we have $S_4/S'_4 = S_4/A_4 \cong C_2$, so we can immediately determine the degree 1 characters, as well as the first column as we know the degrees of all the characters.

S_4	¹ [id]	⁶ [(12)]	⁸ [(123)]	⁶ [(1234)]	³ [(12)(34)]
χ_1	1	1	1	1	1
χ_2	1	-1	1	-1	1
χ_3	2				
χ_4	3				
χ_5	3				

To compute the rest of the character table, we'll usually find a nice representation of the group in practice. Consider the permutation representation $P : S_4 \rightarrow \text{GL}_4(\mathbb{C})$ given by

$$P(\sigma)e_j = e_{\sigma(j)}.$$

Recall that $\chi_P(\sigma)$ is the number of fixed points of $\sigma \in S_4$. For now, let's add χ_P to the character table.

S_4	¹ [id]	⁶ [(12)]	⁸ [(123)]	⁶ [(1234)]	³ [(12)(34)]
χ_1	1	1	1	1	1
χ_2	1	-1	1	-1	1
χ_3	2				
χ_4	3				
χ_5	3				
χ_P	4	2	1	0	0

By Exercise 5 in Homework 3, we find that

$$\langle \chi_P, \chi_P \rangle = \frac{1}{4!} \sum_{\sigma \in S_4} \text{fix}(\sigma)^2 = \frac{1}{24} (1 \cdot 4^2 + 6 \cdot 2^2 + 8 \cdot 1^2 + 6 \cdot 0^2 + 3 \cdot 0^2) = 2,$$

where $\text{fix}(\sigma)$ denotes the number of fixed points of σ . In particular, we see that χ_P is not an irreducible character, but recalling the formula

$$\langle \chi_V, \chi_V \rangle = \sum_{i=1}^s a_i^2,$$

we see that χ_P can be decomposed as the sum of two irreducible components. Now, looking at $\langle \chi_P, \chi_1 \rangle$, we obtain

$$\langle \chi_P, \chi_1 \rangle = \frac{1}{24} (4 \cdot 1 \cdot 1 + 2 \cdot 1 \cdot 6 + 1 \cdot 1 \cdot 8) = 1.$$

This means that $\chi_P = \chi_1 + \chi$, where χ is some irreducible character. In other words, $\chi_P - \chi_1$ is an irreducible character. Notice that $\chi_P(\text{id}) - \chi_1(\text{id}) = 4 - 1 = 3$, so this character is one of χ_4 or χ_5 . Let's say we have $\chi_4 = \chi_P - \chi_1$, since we can just flip the rows if necessary. This allows us to fill out another row in the character table.

S_4	¹ [id]	⁶ [(12)]	⁸ [(123)]	⁶ [(1234)]	³ [(12)(34)]
χ_1	1	1	1	1	1
χ_2	1	-1	1	-1	1
χ_3	2				
χ_4	3	1	0	-1	-1
χ_5	3				
χ_P	4	2	1	0	0

On Question 1 of Homework 4, we will show that if χ is a degree 1 character and for each $d \geq 1$, we let X_d be the set of irreducible characters of degree d , then multiplication by χ permutes X_d for all $d \geq 1$.

In particular, since χ_2 is a degree 1 character, we can multiply χ_4 with χ_2 to obtain the other degree 3 character $\chi_5 = \chi_4 \cdot \chi_2$, as multiplication by χ_2 permutes $X_3 = \{\chi_4, \chi_5\}$. Similarly, if we multiply χ_5 with χ_2 , we again obtain χ_4 .

S_4	¹ [id]	⁶ [(12)]	⁸ [(123)]	⁶ [(1234)]	³ [(12)(34)]
χ_1	1	1	1	1	1
χ_2	1	-1	1	-1	1
χ_3	2				
χ_4	3	1	0	-1	-1
χ_5	3	-1	0	1	-1
χ_P	4	2	1	0	0

What happens if we do this with χ_3 ? We have $X_2 = \{\chi_3\}$, and we know that multiplication by χ_2 must permute X_2 , so that $\chi_3 \cdot \chi_2 = \chi_3$. This tells us that $\chi_3((12)) = \chi_3((1234)) = 0$, since $\chi_2((12)) = \chi_2((1234)) = -1$. Let's now try to find the remaining entries in the row.

S_4	¹ [id]	⁶ [(12)]	⁸ [(123)]	⁶ [(1234)]	³ [(12)(34)]
χ_1	1	1	1	1	1
χ_2	1	-1	1	-1	1
χ_3	2	0	a	0	b
χ_4	3	1	0	-1	-1
χ_5	3	-1	0	1	-1
χ_P	4	2	1	0	0

We take the inner product of χ_3 with some of the other irreducible characters. Observe that

$$0 = \langle \chi_3, \chi_1 \rangle = \frac{1}{24}(2 \cdot 1 \cdot 1 + a \cdot 1 \cdot 8 + b \cdot 1 \cdot 3) = \frac{1}{24}(2 + 8a + 3b),$$

$$0 = \langle \chi_3, \chi_4 \rangle = \frac{1}{24}(2 \cdot 3 \cdot 1 + a \cdot 0 \cdot 8 + b \cdot (-1) \cdot 3) = \frac{1}{24}(6 - 3b).$$

Solving this yields $a = -1$ and $b = 2$, so we have now completed the character table of S_4 .

S_4	¹ [id]	⁶ [(12)]	⁸ [(123)]	⁶ [(1234)]	³ [(12)(34)]
χ_1	1	1	1	1	1
χ_2	1	-1	1	-1	1
χ_3	2	0	-1	0	2
χ_4	3	1	0	-1	-1
χ_5	3	-1	0	1	-1

EXAMPLE 19.2

Let's now find the character table of S_5 . Note that S_5 has 7 conjugacy classes; their sizes are

$$\begin{aligned} \#[\text{id}] &= 1, \\ \#[(12)] &= 10, \\ \#[(123)] &= 20, \\ \#[(1234)] &= 30, \\ \#[(12345)] &= 24, \\ \#[(12)(34)] &= 15, \\ \#[(12)(345)] &= 20. \end{aligned}$$

These sizes can be determined using Exercise 6 of Homework 3. This states that if $\sigma \in S_n$ has disjoint cycle structure with $\lambda_i \geq 0$ i -cycles for $i = 1, \dots, n$ (so that $\sum_{i=1}^n i\lambda_i = n$), then the conjugacy class of σ has size

$$\frac{n!}{\prod_{i=1}^n \lambda_i! i^{\lambda_i}}.$$

Now, we recall that $S'_5 = A_5$, so $S_5/S'_5 = S_5/A_5 \cong C_2$. Then the odd cycles get sent to -1 and the even cycles get sent to 1 , so we obtain the first two rows of the character table.

S_5	¹ [id]	¹⁰ [(12)]	²⁰ [(123)]	³⁰ [(1234)]	²⁴ [(12345)]	¹⁵ [(12)(34)]	²⁰ [(12)(345)]
χ_1	1	1	1	1	1	1	1
χ_2	1	-1	1	-1	1	1	-1
χ_3							
χ_4							
χ_5							
χ_6							
χ_7							

Take the permutation representation $P : S_5 \rightarrow \text{GL}_5(\mathbb{C})$ given by

$$P(\sigma)e_j = e_{\sigma(j)}.$$

Again, $\chi_P(\sigma)$ gives the number of fixed points of σ , so let's add χ_P to the character table for now.

S_5	¹ [id]	¹⁰ [(12)]	²⁰ [(123)]	³⁰ [(1234)]	²⁴ [(12345)]	¹⁵ [(12)(34)]	²⁰ [(12)(345)]
χ_1	1	1	1	1	1	1	1
χ_2	1	-1	1	-1	1	1	-1
χ_3							
χ_4							
χ_5							
χ_6							
χ_7							
χ_P	5	3	2	1	0	1	0

By Exercise 5 of Homework 3, we have

$$\langle \chi_P, \chi_P \rangle = \frac{1}{5!} \sum_{\sigma \in S_5} \text{fix}(\sigma)^2 = 2.$$

We compute that

$$\langle \chi_P, \chi_1 \rangle = \frac{1}{5!} (5 \cdot 1 \cdot 1 + 3 \cdot 1 \cdot 10 + 2 \cdot 1 \cdot 20 + 1 \cdot 1 \cdot 30 + 1 \cdot 1 \cdot 15) = 1.$$

As in the previous example, this tells us that $\chi_P - \chi_1$ is an irreducible character. Since $\chi_P(\text{id}) - \chi_1(\text{id}) = 5 - 1 = 4$, we obtain an irreducible character $\chi_3 = \chi_P - \chi_1$ of degree 4.

S_5	¹ [id]	¹⁰ [(12)]	²⁰ [(123)]	³⁰ [(1234)]	²⁴ [(12345)]	¹⁵ [(12)(34)]	²⁰ [(12)(345)]
χ_1	1	1	1	1	1	1	1
χ_2	1	-1	1	-1	1	1	-1
χ_3	4	2	1	0	-1	0	-1
χ_4							
χ_5							
χ_6							
χ_7							
χ_P	5	3	2	1	0	1	0

We can also take $\chi_4 = \chi_3 \cdot \chi_2$ to get another irreducible character.

S_5	¹ [id]	¹⁰ [(12)]	²⁰ [(123)]	³⁰ [(1234)]	²⁴ [(12345)]	¹⁵ [(12)(34)]	²⁰ [(12)(345)]
χ_1	1	1	1	1	1	1	1
χ_2	1	-1	1	-1	1	1	-1
χ_3	4	2	1	0	-1	0	-1
χ_4	4	-2	1	0	-1	0	1
χ_5							
χ_6							
χ_7							
χ_P	5	3	2	1	0	1	0

Now, let $a = \chi_5(\text{id})$, $b = \chi_6(\text{id})$, and $c = \chi_7(\text{id})$. Then we know that

$$1^2 + 1^2 + 4^2 + 4^2 + a^2 + b^2 + c^2 = 120,$$

or equivalently,

$$a^2 + b^2 + c^2 = 86.$$

Therefore, we have $2 \leq a, b, c \leq 9$, and we can deduce that $(a, b, c) = (5, 5, 6)$. We have $X_6 = \{\chi_7\}$, and since χ_2 is of degree 1, we have $\chi_7 \cdot \chi_2 = \chi_7$, which tells us that $\chi_7((12)) = \chi((1234)) = \chi((12)(345)) = 0$, since their counterparts in χ_2 are equal to -1. We can now fill out the first column and some of the entries of χ_7 .

S_5	¹ [id]	¹⁰ [(12)]	²⁰ [(123)]	³⁰ [(1234)]	²⁴ [(12345)]	¹⁵ [(12)(34)]	²⁰ [(12)(345)]
χ_1	1	1	1	1	1	1	1
χ_2	1	-1	1	-1	1	1	-1
χ_3	4	2	1	0	-1	0	-1
χ_4	4	-2	1	0	-1	0	1
χ_5	5						
χ_6	5						
χ_7	6	0		0			0
χ_P	5	3	2	1	0	1	0

Observe that S_5 acts on the subsets of size 2; namely $\{\{i, j\} : i, j \in \{1, 2, 3, 4, 5\}\}$. There are $\binom{5}{2} = 10$ such subsets. Instead of considering the permutation representation $P : S_5 \rightarrow \text{GL}_5(\mathbb{C})$, we have another representation $Q : S_5 \rightarrow \text{GL}_{10}(\mathbb{C})$ where from the basis $\{e_{\{i, j\}} : i, j \in \{1, 2, 3, 4, 5\}\}$, we define

$$\sigma \cdot e_{\{i, j\}} = e_{\sigma(i)\sigma(j)}.$$

Let's now determine χ_Q . This time, $\chi_Q(\sigma)$ is the number of sets of size two that are fixed by σ .

S_5	¹ [id]	¹⁰ [(12)]	²⁰ [(123)]	³⁰ [(1234)]	²⁴ [(12345)]	¹⁵ [(12)(34)]	²⁰ [(12)(345)]
χ_1	1	1	1	1	1	1	1
χ_2	1	-1	1	-1	1	1	-1
χ_3	4	2	1	0	-1	0	-1
χ_4	4	-2	1	0	-1	0	1
χ_5	5						
χ_6	5						
χ_7	6	0		0			0
χ_Q	10	4	1	0	0	2	1

For example, note that $(12) \cdot e_{\{1,2\}} = e_{\{1,2\}}$, because the set $\{2, 1\}$ is the same as the set $\{1, 2\}$. Then, we see that the basis elements fixed by (12) are $e_{\{1,2\}}$, $e_{\{3,4\}}$, $e_{\{3,5\}}$, and $e_{\{4,5\}}$, so $\chi_Q((12)) = 4$. The other values of χ_Q can be found similarly. We now compute that

$$\langle \chi_Q, \chi_Q \rangle = \frac{1}{5!}(1 \cdot 10^2 + 10 \cdot 4^2 + 20 \cdot 1^2 + 15 \cdot 2^2 + 20 \cdot 1^2) = 3.$$

Therefore, χ_Q is the sum of 3 distinct irreducible characters. We find that

$$\langle \chi_Q, \chi_1 \rangle = \frac{1}{5!}(10 \cdot 1 \cdot 1 + 4 \cdot 1 \cdot 10 + 1 \cdot 1 \cdot 20 + 2 \cdot 1 \cdot 15 + 1 \cdot 1 \cdot 20) = 1,$$

$$\langle \chi_Q, \chi_3 \rangle = \frac{1}{5!}(10 \cdot 4 \cdot 1 + 4 \cdot 2 \cdot 10 + 1 \cdot 1 \cdot 20 + 1 \cdot (-1) \cdot 20) = 1.$$

Hence, $\chi_Q - \chi_1 - \chi_3$ is an irreducible character. Note that $\chi_Q(\text{id}) - \chi_1(\text{id}) - \chi_3(\text{id}) = 10 - 1 - 4 = 5$, and since $\chi_5(\text{id}) = 5$, we can set $\chi_5 = \chi_Q - \chi_1 - \chi_3$. Then, $X_5 = \{\chi_5, \chi_6\}$, and since χ_2 is a degree 1 character, it must permute X_5 , so we can set $\chi_6 = \chi_5 \cdot \chi_2$. This completes two more rows of the character table.

S_5	¹ [id]	¹⁰ [(12)]	²⁰ [(123)]	³⁰ [(1234)]	²⁴ [(12345)]	¹⁵ [(12)(34)]	²⁰ [(12)(345)]
χ_1	1	1	1	1	1	1	1
χ_2	1	-1	1	-1	1	1	-1
χ_3	4	2	1	0	-1	0	-1
χ_4	4	-2	1	0	-1	0	1
χ_5	5	1	-1	-1	0	1	1
χ_6	5	-1	-1	1	0	1	-1
χ_7	6	0	d	0	e	f	0
χ_Q	10	4	1	0	0	2	1

Finally, let's compute χ_7 by determining $d = \chi_7((123))$, $e = \chi_7((12345))$, and $f = \chi_7((12)(34))$. We have

$$0 = \langle \chi_7, \chi_5 \rangle = \frac{1}{5!}(30 - 20d + 15f),$$

$$0 = \langle \chi_7, \chi_3 \rangle = \frac{1}{5!}(24 + 20d - 24e),$$

$$0 = \langle \chi_7, \chi_1 \rangle = \frac{1}{5!}(6 + 20d + 24e + 15f).$$

This is a system of 3 equations and 3 unknowns; solving it yields $(d, e, f) = (0, 1, -2)$, completing the character table of S_5 .

S_5	¹ [id]	¹⁰ [(12)]	²⁰ [(123)]	³⁰ [(1234)]	²⁴ [(12345)]	¹⁵ [(12)(34)]	²⁰ [(12)(345)]
χ_1	1	1	1	1	1	1	1
χ_2	1	-1	1	-1	1	1	-1
χ_3	4	2	1	0	-1	0	-1
χ_4	4	-2	1	0	-1	0	1
χ_5	5	1	-1	-1	0	1	1
χ_6	5	-1	-1	1	0	1	-1
χ_7	6	0	0	0	1	-2	0

20 Algebraic numbers and algebraic integers (10/29/2021)

Write $\mathbb{C}[G] \cong M_{n_1}(\mathbb{C}) \times \cdots \times M_{n_s}(\mathbb{C})$, and let χ_1, \dots, χ_s be the irreducible characters. We have $\chi_i(1_G) = n_i$, which is the degree of χ_i . Moreover, since $\langle \chi_i, \chi_j \rangle = \delta_{ij}$, we know that $\|\chi\|^2 = 1$ if and only if χ is irreducible. In particular, if the character $\chi = a_1\chi_1 + \cdots + a_s\chi_s$ is irreducible, then

$$\|\chi\|^2 = a_1^2 + \cdots + a_s^2 = 1$$

implies that there is a unique $1 \leq j \leq s$ such that $a_j = 1$ and $a_i = 0$ for all $i \neq j$. Hence, $\|\chi\|^2 = 1$ if and only if $\chi = \chi_j$ for some $1 \leq j \leq s$. Today, we'll introduce the algebraic integers, which will help us to prove the last part of the big theorem, which states that $n_i \mid |G|$ for all $1 \leq i \leq s$.

DEFINITION 20.1

We define the **algebraic numbers** $\mathbb{A} \subseteq \mathbb{C}$ to be the set

$$\mathbb{A} = \{\alpha \in \mathbb{C} : P(\alpha) = 0 \text{ for some monic polynomial } P(x) \in \mathbb{Z}[x]\}.$$

EXAMPLE 20.2

- (1) Observe that $\mathbb{Z} \subseteq \mathbb{A}$, since for any $n \in \mathbb{Z}$, the polynomial $P(x) = x - n$ has n as a root.
- (2) If $\alpha \in \mathbb{Q}$, then $\beta = e^{\pi i \alpha} \in \mathbb{A}$. Indeed, write $\alpha = a/b$ for some $a, b \in \mathbb{Z}$ with $b \neq 0$. Taking the polynomial $P(x) = x^{2b-1}$, we have $P(\beta) = (e^{\pi i a/b})^{2b} - 1 = e^{2\pi i a} - 1 = 0$.
- (3) Let $a \in \mathbb{Z}$ and $b \in \mathbb{Z}^+$. Then $\alpha = \sqrt[b]{a} \in \mathbb{A}$ by taking $P(x) = x^b - a \in \mathbb{Z}[x]$.

LEMMA 20.3

We have $\mathbb{A} \cap \mathbb{Q} = \mathbb{Z}$.

PROOF. It is clear that $\mathbb{Z} \subseteq \mathbb{A} \cap \mathbb{Q}$. On the other hand, we have $\alpha = 0 \in \mathbb{Z}$. Suppose that we have a nonzero $\alpha = a/b$ with $\gcd(a, b) = 1$ and $b > 0$ which is a root of the monic polynomial

$$x^n + c_{n-1}x^{n-1} + \cdots + c_1x + c_0 \in \mathbb{Z}[x].$$

Moreover, we can assume that $c_0 \neq 0$, for otherwise we could just reduce the degree of the polynomial. Then by the rational roots theorem, we obtain $b \mid 1$ and $a \mid c_0$, which implies that $\alpha = a/b \in \mathbb{Z}$. Therefore, we conclude that $\mathbb{A} \cap \mathbb{Q} = \mathbb{Z}$. \square

This statement is very simple, but it has some very powerful consequences. Recall that a finitely generated \mathbb{Z} -submodule of $(\mathbb{C}, +)$ is given by all elements of the form

$$\{n_1\lambda_1 + \cdots + n_p\lambda_p : n_1, \dots, n_p \in \mathbb{Z}\}$$

for some fixed $\lambda_1, \dots, \lambda_p \in \mathbb{C}$. For example, we have $\mathbb{Z}[i] = \{a + bi : a, b \in \mathbb{Z}\}$ by choosing $\lambda_1 = 1$ and $\lambda_2 = i$. We'll now prove some characterizations of algebraic numbers.

THEOREM 20.4

Let $\alpha \in \mathbb{C}$. The following are equivalent:

- (1) $\alpha \in \mathbb{A}$.
- (2) There exists a nonzero finitely generated \mathbb{Z} -submodule M of \mathbb{C} such that $\alpha M \subseteq M$.
- (3) There exists $p \geq 1$ and $\lambda_1, \dots, \lambda_p \in \mathbb{C} \setminus \{0\}$ such that $\alpha \lambda_i \in \mathbb{Z} \lambda_1 + \dots + \mathbb{Z} \lambda_p$ for all $i = 1, \dots, p$.

PROOF. (1) \Rightarrow (2). If $\alpha \in \mathbb{A}$, then there exists $n \geq 1$ and $c_0, \dots, c_{n-1} \in \mathbb{Z}$ such that

$$\alpha^n + c_{n-1}\alpha^{n-1} + \dots + c_1\alpha + c_0 = 0. \quad (20.1)$$

Let $M = \mathbb{Z} + \mathbb{Z}\alpha + \mathbb{Z}\alpha^2 + \dots + \mathbb{Z}\alpha^{n-1}$. This is a finitely generated \mathbb{Z} -submodule, and $M \neq (0)$ since $1 \in M$. Now, we claim that $\alpha M \subseteq M$. To this end, suppose that $a_0 + a_1\alpha + \dots + a_{n-1}\alpha^{n-1} \in M$. Then we have

$$\begin{aligned} \alpha(a_0 + a_1\alpha + \dots + a_{n-1}\alpha^{n-1}) &= a_0\alpha + a_1\alpha^2 + \dots + a_{n-2}\alpha^{n-1} + a_{n-1}\alpha^n \\ &= a_0\alpha + a_1\alpha^2 + \dots + a_{n-2}\alpha^{n-1} + a_{n-1}(-c_{n-1}\alpha^{n-1} - \dots - c_1\alpha - c_0) \\ &= -a_{n-1}c_0 + (a_0 - a_{n-1}c_1)\alpha + \dots + (a_{n-2} - a_{n-1}c_{n-1})\alpha^{n-1}, \end{aligned}$$

where the second last equality follows from (20.1). We see that $\alpha(a_0 + a_1\alpha + \dots + a_{n-1}\alpha^{n-1}) \in M$, so $\alpha M \subseteq M$.

(2) \Rightarrow (3). Suppose there exists a nonzero finitely generated \mathbb{Z} -submodule M of \mathbb{C} such that $\alpha M \subseteq M$. Then we can pick $\lambda_1, \dots, \lambda_p \in \mathbb{C} \setminus \{0\}$ such that $M = \mathbb{Z}\lambda_1 + \dots + \mathbb{Z}\lambda_p$. Since $\alpha M \subseteq M$, this implies that $\alpha \lambda_i \in M$ for each $i = 1, \dots, p$.

(3) \Rightarrow (1). Suppose there exists $p \geq 1$ and $\lambda_1, \dots, \lambda_p \in \mathbb{C} \setminus \{0\}$ such that $\alpha \lambda_i \in \mathbb{Z} \lambda_1 + \dots + \mathbb{Z} \lambda_p$ for all $i = 1, \dots, p$. Then for $j = 1, \dots, p$, we can pick $a_{j1}, \dots, a_{jp} \in \mathbb{Z}$ such that

$$\alpha \lambda_i = a_{j1}\lambda_1 + \dots + a_{jp}\lambda_p.$$

We can write this as a matrix equation to get

$$\alpha \begin{pmatrix} \lambda_1 \\ \lambda_2 \\ \vdots \\ \lambda_p \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & \dots & a_{1p} \\ a_{21} & a_{22} & \dots & a_{2p} \\ \vdots & \vdots & \ddots & \vdots \\ a_{p1} & a_{p2} & \dots & a_{pp} \end{pmatrix} \begin{pmatrix} \lambda_1 \\ \lambda_2 \\ \vdots \\ \lambda_p \end{pmatrix}.$$

Set $v = (\lambda_1, \dots, \lambda_p)^T$, and notice that $v \neq 0$ since $\lambda_1, \dots, \lambda_p \in \mathbb{C} \setminus \{0\}$. Moreover, set A to be the matrix above, and observe that $A \in M_p(\mathbb{Z})$. Now, we have $\alpha v = Av$, so α is an eigenvalue of A . Hence, α is a root of the characteristic polynomial of A . That is, for

$$P_A(x) = \det(xI - A) = \det \begin{pmatrix} x - a_{11} & \dots & -a_{1p} \\ \vdots & \ddots & \vdots \\ -a_{p1} & \dots & x - a_{pp} \end{pmatrix},$$

we have $P_A(\alpha) = 0$. Note that $A \in M_p(\mathbb{Z})$, so $P_A(x)$ is a monic polynomial in $\mathbb{Z}[x]$. It follows that $\alpha \in \mathbb{A}$. \square

THEOREM 20.5

The algebraic numbers \mathbb{A} form a subring of \mathbb{C} .

PROOF. It suffices to show that \mathbb{A} is closed under addition and multiplication, and that $-1 \in \mathbb{A}$; this last condition assures that we have additive inverses.

We have already seen that $\mathbb{Z} \subseteq \mathbb{A}$, so $-1 \in \mathbb{A}$. Let $\alpha, \beta \in \mathbb{A}$. We assume that α and β are both nonzero, as the result is trivial otherwise. We want to show that $\alpha + \beta$ and $\alpha\beta$ are in \mathbb{A} . By definition, we have

$$\begin{aligned}\alpha^n + c_{n-1}\alpha^{n-1} + \cdots + c_1\alpha + c_0 &= 0, \\ \beta^m + d_{m-1}\beta^{m-1} + \cdots + d_1\beta + d_0 &= 0,\end{aligned}$$

for some $c_0, \dots, c_{n-1}, d_0, \dots, d_{m-1} \in \mathbb{Z}$. Let

$$M = \sum_{i=0}^{n-1} \sum_{j=0}^{m-1} \mathbb{Z}\alpha^i\beta^j,$$

which is a finitely generated \mathbb{Z} -submodule of \mathbb{C} , and $M \neq (0)$ since $1 \in M$. Now, we claim that $\alpha M \subseteq M$ and $\beta M \subseteq M$. It suffices to show that $\beta(\alpha^i\beta^j)$ and $\alpha(\alpha^i\beta^j)$ are in M for all $0 \leq i \leq n-1$ and $0 \leq j \leq m-1$.

We will consider $\alpha(\alpha^i\beta^j)$. When $0 \leq i \leq n-2$, we have $\alpha(\alpha^i\beta^j) = \alpha^{i+1}\beta^j \in M$, since $0 \leq i+1 \leq n-1$. Otherwise, we have $i = n-1$, in which case

$$\alpha(\alpha^{n-1}\beta^j) = \alpha^n\beta^j = (-c_{n-1}\alpha^{n-1} - \cdots - c_1\alpha - c_0)\beta^j \in M.$$

This implies that $\alpha M \subseteq M$, and a similar argument shows that $\beta M \subseteq M$. Now, observe that

$$(\alpha + \beta)M \subseteq \alpha M + \beta M \subseteq M + M = M,$$

and similarly, we know from our work above that

$$(\alpha\beta)M = \alpha(\beta M) \subseteq \alpha M \subseteq M.$$

It follows from Theorem 20.4 that $\alpha + \beta$ and $\alpha\beta$ are in \mathbb{A} . □

REMARK 20.6

Note that \mathbb{A} is not a field, since $2 \in \mathbb{A}$ but $1/2 \notin \mathbb{A}$.

Now, we'll prove an interesting corollary of the fact that \mathbb{A} is a subring of \mathbb{C} .

COROLLARY 20.7

If $\alpha \in \mathbb{Q}$ and $\tan(\pi\alpha) \in \mathbb{Q}$, then $\tan(\pi\alpha) \in \{0, 1, -1\}$.

PROOF. Recall that $\tan^2(x) + 1 = 1/\cos^2(x)$. Therefore, if $\tan(\pi\alpha) \in \mathbb{Q}$, then we have $\tan^2(\pi\alpha) + 1 = 1/\cos^2(\pi\alpha) \in \mathbb{Q}$ as well. This implies that $4\cos^2(\pi\alpha) \in \mathbb{Q}$. Now, notice that

$$4\cos^2(\pi\alpha) = (2\cos(\pi\alpha))^2 = (e^{i\pi\alpha} + e^{-i\pi\alpha})^2.$$

In particular, since $e^{i\pi\alpha}$ and $e^{-i\pi\alpha}$ are both algebraic numbers (as we saw in Example 20.2), this shows that $4\cos^2(\pi\alpha) \in \mathbb{Q} \cap \mathbb{A} = \mathbb{Z}$. Now, we know that $4\cos^2(\pi\alpha) \in \{0, 1, 2, 3, 4\}$. Taking the inverses and multiplying by 4, we find that $1/\cos^2(\pi\alpha) \in \{4, 2, 4/3, 1\}$. Finally, we have

$$\tan^2(\pi\alpha) = \frac{1}{\cos^2(\pi\alpha)} - 1 \in \left\{3, 1, \frac{1}{3}, 0\right\}.$$

But we assumed that $\tan(\pi\alpha) \in \mathbb{Q}$, so the only possibilities are $\tan(\pi\alpha) \in \{0, 1, -1\}$, as desired. □

21 Degree of irreps divide order of the group (11/01/2021)

Let G be a finite group. Let $\rho : \mathbb{C}[G] \rightarrow M_{n_1}(\mathbb{C}) \times \cdots \times M_{n_s}(\mathbb{C})$ be a \mathbb{C} -algebra isomorphism. Then, we have the following commutative diagram.

$$\begin{array}{ccc} \mathbb{C}[G] & \xrightarrow{\rho} & M_{n_1}(\mathbb{C}) \times \cdots \times M_{n_s}(\mathbb{C}) \\ & \searrow \rho_i = \pi_i \circ \rho & \downarrow \pi_i \\ & & M_{n_i}(\mathbb{C}) \end{array}$$

Then, we obtain characters $\chi_i(g) = \text{Tr}(\rho_i(g))$. We also have $\mathbb{C}[G]$ -modules $V_i = \mathbb{C}^{n_i \times 1}$ with the action $g \cdot v = \rho_i(g) \cdot v$. Our goal in this lecture is to prove that $n_i \mid |G|$ for each $i = 1, \dots, s$, where $\chi_i(1_G) = n_i$ is the degree of the character. Note that $\rho_i(1_G) = I_{n_i}$.

LEMMA 21.1

Let \mathcal{C} be a conjugacy class of G , and let $g \in \mathcal{C}$. Then for all $i = 1, \dots, s$, we have

$$\frac{|\mathcal{C}| \chi_i(g)}{n_i} \in \mathbb{A}.$$

PROOF. Let $\mathcal{C}_1, \dots, \mathcal{C}_s$ be the conjugacy classes of G . Recall from Proposition 10.7 that a basis for $Z(\mathbb{C}[G])$ is given by z_1, \dots, z_s , where

$$z_p = \sum_{h \in \mathcal{C}_p} h.$$

Let $M = \mathbb{Z}z_1 + \cdots + \mathbb{Z}z_s \subseteq Z(\mathbb{C}[G])$. We claim that $z_p M \subseteq M$ for all $p = 1, \dots, s$.

It suffices to show that $z_p z_j \in M$ for all $p = 1, \dots, s$ and $j = 1, \dots, s$, as every element in M can be written as a linear combination of z_1, \dots, z_s . In particular, notice that

$$z_p(c_1 z_1 + \cdots + c_s z_s) = c_1 z_p z_1 + \cdots + c_s z_p z_s \in M.$$

Notice that $z_p z_j \in Z(\mathbb{C}[G])$, so we have

$$z_p z_j = \sum_{k=1}^s \lambda_{p,j,k} z_k \tag{21.1}$$

for some $\lambda_{p,j,k} \in \mathbb{C}$. In order to show that $z_p z_j \in M$, we require that $\lambda_{p,j,k} \in \mathbb{Z}$ for all $k = 1, \dots, s$. Pick $h \in \mathcal{C}_k$ and consider the coefficient of h in (21.1). On the right hand side, it is simply $\lambda_{p,j,k}$. On the left hand side, note that

$$z_p z_j = \left(\sum_{h' \in \mathcal{C}_p} h' \right) \left(\sum_{h'' \in \mathcal{C}_j} h'' \right),$$

so the coefficient of h is $\#\{(h', h'') \in \mathcal{C}_p \times \mathcal{C}_j : h' \cdot h'' = h\} \in \mathbb{Z}_{\geq 0}$. This proves the claim.

Now, consider the diagram above, and note that ρ_i is surjective. Since z_j is central in $\mathbb{C}[G]$, we see that $\rho_i(z_j) \in Z(M_{n_i}(\mathbb{C}))$. By surjectivity of ρ_i , it follows that $\rho_i(z_j) = \gamma_{i,j} I_{n_i}$ with $\gamma_{i,j} \in \mathbb{C}$; that is, $\rho_i(z_j)$ is a scalar matrix. Next, define

$$M_i = \mathbb{Z}\gamma_{i,1} + \cdots + \mathbb{Z}\gamma_{i,s} \subseteq \mathbb{C},$$

which is a finitely generated \mathbb{Z} -submodule of \mathbb{C} with $M_i \neq (0)$. Notice that $M_i = \rho_i(M)$ by construction after identifying the scalar matrices $\mathbb{C} \cdot I_{n_i}$ with \mathbb{C} . Now, since $z_j M \subseteq M$ by our claim, we obtain $\rho_i(z_j) \rho_i(M) \subseteq \rho_i(M)$, so

$$\gamma_{i,j} M_i \subseteq M_i$$

after identification. Hence, for all $1 \leq i, j \leq s$, we get $\gamma_{i,j} \in \mathbb{A}$. Next, let $\mathcal{C} = \mathcal{C}_j$ be a conjugacy class and $g \in \mathcal{C}$. Note that

$$\gamma_{i,j} I_{n_i} = \rho_i(z_j) = \rho_i \left(\sum_{h \in \mathcal{C}_j} h \right) = \sum_{h \in \mathcal{C}_j} \rho_i(h).$$

Taking the trace of both sides yields

$$\gamma_{i,j} \cdot n_i = \text{Tr}(\gamma_{i,j} I_{n_i}) = \text{Tr} \left(\sum_{h \in \mathcal{C}_j} \rho_i(h) \right) = \sum_{h \in \mathcal{C}_j} \chi_i(h) = |\mathcal{C}| \chi_i(g),$$

where the last equality is because χ_i is a class function. It follows that

$$\frac{|\mathcal{C}| \chi_i(g)}{n_i} = \gamma_{i,j} \in \mathbb{A}. \quad \square$$

THEOREM 21.2

Let G be a finite group. If χ_i is an irreducible character with degree n_i , then $n_i \mid |G|$.

PROOF. We always have a trivial irreducible character with $\chi(h) = 1$ for all $h \in G$. Without loss of generality, suppose that χ_1 is the trivial representation, which has degree $n_1 = 1$, in which case the result clearly holds.

It suffices to consider the case where $i > 1$. Let $\mathcal{C}_1, \dots, \mathcal{C}_s$ be the conjugacy classes of G . For each $j = 1, \dots, s$, pick a representative $g_j \in \mathcal{C}_j$. Then we have

$$1 = \langle \chi_i, \chi_i \rangle = \frac{1}{|G|} \sum_{j=1}^s |\mathcal{C}_j| \chi_i(g_j) \overline{\chi_i(g_j)} = \frac{n_i}{|G|} \sum_{j=1}^s \frac{|\mathcal{C}_j| \chi_i(g_j)}{n_i} \cdot \overline{\chi_i(g_j)}.$$

By Lemma 21.1, each $|\mathcal{C}_j| \chi_i(g_j)/n_i$ is in \mathbb{A} . Moreover, we have shown that $\rho_i(g)$ is triangularizable with roots of unity $\omega_1, \dots, \omega_{n_i}$ along the diagonal, so

$$\overline{\chi_i(g_j)} = \overline{\omega_1} + \dots + \overline{\omega_{n_i}} \in \mathbb{A}.$$

In particular, we see that

$$1 = \frac{n_i}{|G|} \cdot \alpha$$

where $\alpha \in \mathbb{A}$. Rearranging gives $|G|/n_i = \alpha$. Observe that $|G|/n_i \in \mathbb{Q} \cap \mathbb{A} = \mathbb{Z}$, so $n_i \mid |G|$. \square

22 Burnside's theorem (11/03/2021)

The fact that the degrees of the irreducible characters divide the order of the group has some very powerful consequences. The Feit-Thompson theorem states that every group of odd order is solvable. We'll focus on Burnside's theorem, which gives the weaker statement that every group of order $p^a q^b$ is solvable, where p and q are distinct primes and $a, b \in \mathbb{Z}^+$. The proofs of these theorems are very difficult (if not impossible) without using character theory, and we'll use it to make our lives easier. First, let's recall what it means for a group to be solvable.

DEFINITION 22.1

A group G is **solvable** if there exists a tower

$$G = G_0 \supseteq G_1 \supseteq G_2 \supseteq \cdots \supseteq G_m = \{1\}$$

such that $G_{i+1} \trianglelefteq G_i$ and G_i/G_{i+1} is abelian for all $0 \leq i \leq m-1$.

Towards the proof of Burnside's theorem, we'll first prove some intermediate results.

LEMMA 22.2

Let χ be an irreducible character of degree $n \geq 2$. If $\chi(g)/n \in \mathbb{A}$ for some $g \in G$, then $\chi(g) = 0$.

We leave the proof of this for later. For the moment, we will use this lemma to prove the following theorem.

THEOREM 22.3

Let G be a non-abelian finite group. Suppose that G has a conjugacy class of size p^a where p is a prime and $a \in \mathbb{Z}^+$. Then G is not simple.

PROOF. Suppose by way of contradiction that there exists a non-abelian finite simple group G with an element $g \in G$ such that the conjugacy class $\mathcal{C} = \mathcal{C}(g)$ containing g has size p^a , where p is prime and $a \in \mathbb{Z}^+$. Since G is non-abelian and simple, we have $G' = G$. Indeed, note that $G' \trianglelefteq G$. By simplicity, we either have $G' = G$ or $G' = \{1\}$. But G is non-abelian, so we must be in the first case. This means that G has one inequivalent irreducible representation of degree 1 since $|G/G'| = |G/G| = 1$. The only irreducible character of degree 1 is the trivial character χ with $\chi(h) = 1$ for all $h \in G$.

Let χ_1, \dots, χ_s be the irreducible characters of G . Without loss of generality, we may assume that χ_1 is the trivial character. Notice that if n_1, \dots, n_s are the degrees of χ_1, \dots, χ_s respectively, then $n_1 = 1$ and $n_i > 1$ for $i = 2, \dots, s$. Recall that we have $g \in G$ such that $|\mathcal{C}| = |\mathcal{C}(g)| = p^a$, where p is prime and $a \in \mathbb{Z}^+$. This implies that $g \neq 1$, for otherwise its conjugacy class would have size 1. Now, if L is the left regular representation of G , then $\chi_L(g) = 0$. This implies that

$$0 = \chi_L(g) = \sum_{i=1}^s n_i \chi_i(g) = \chi_1(g) + \sum_{\substack{i \geq 2 \\ p \nmid n_i}} n_i \chi_i(g) + \sum_{\substack{i \geq 2 \\ p \nmid n_i}} n_i \chi_i(g).$$

CLAIM. For $i \geq 2$, if $p \nmid n_i$, then $\chi_i(g) = 0$.

PROOF OF CLAIM. We know that $\chi_i(g) \in \mathbb{A}$. We have also showed in Lemma 21.1 that

$$\frac{p^a \chi_i(g)}{n_i} = \frac{|\mathcal{C}(g)| \chi_i(g)}{n_i} \in \mathbb{A}.$$

Since $p \nmid n_i$, we have $\gcd(p^a, n_i) = 1$. Therefore, there exist $c, d \in \mathbb{Z}$ such that $cp^a + dn_i = 1$. We find that

$$\frac{\chi_i(g)}{n_i} = \frac{cp^a + dn_i}{n_i} \chi_i(g) = \frac{cp^a \chi_i(g)}{n_i} + d \chi_i(g) \in \mathbb{A}.$$

By Lemma 22.2, we obtain $\chi_i(g) = 0$. ■

Now, writing $n_i = pn'_i$ for each $i \geq 2$ with $p \mid n_i$, we have

$$0 = \chi_1(g) + \sum_{\substack{i \geq 2 \\ p \mid n_i}} n_i \chi_i(g) + \sum_{\substack{i \geq 2 \\ p \nmid n_i}} n_i \chi_i(g) = \chi_1(g) + p \sum_{\substack{i \geq 2 \\ p \mid n_i}} n'_i \chi_i(g).$$

Let α denote the sum in the above equation, and note that $\alpha \in \mathbb{A}$. Then $1 + p\alpha = 0$, which implies that $\alpha = -1/p$. But this is a contradiction since $\mathbb{Q} \cap \mathbb{A} = \mathbb{Z}$, but $-1/p \notin \mathbb{Z}$. \square

We can now prove Burnside's theorem. First, we'll recall some facts from group theory.

- (1) Let $N \trianglelefteq G$. Then G is solvable if and only if N and G/N are both solvable.
- (2) Let G be a group of order $q^b c$ where q is prime, $b \in \mathbb{Z}^+$, and $q \nmid c$. Then by the first Sylow theorem, G has a subgroup Q of order q^b .
- (3) If G is a group of order q^b where q is prime and $b \in \mathbb{Z}^+$, then G has a non-trivial center by the class equation.
- (4) If $g \in G$ and $\mathcal{C}(g)$ is the conjugacy class of g , then $|\mathcal{C}(g)| = |G|/|C(g)|$, where $C(g) = \{h \in G : hg = gh\}$ is the centralizer of g .

THEOREM 22.4: BURNSIDE'S THEOREM

Let G be a group of order $p^a q^b$ where p and q are distinct primes and $a, b \in \mathbb{Z}^+$. Then G is solvable.

PROOF. Suppose the result is not true. Let G be a minimal counterexample; that is, G is a group of order $p^a q^b$ where p and q are distinct primes and $a, b \in \mathbb{Z}^+$, and G has minimal size with respect to this property.

CLAIM. G is a non-abelian simple group.

PROOF OF CLAIM. Note that G is non-abelian since if G were abelian, then it would be solvable. Assume that G is not simple. Then there exists a non-trivial proper normal subgroup N of G . Then G/N and N are both smaller than G and their sizes divide $p^a q^b$. By minimality, N and G/N are solvable, so G is also solvable by (1), a contradiction. \blacksquare

Pick a subgroup $Q \leq G$ with $|Q| = q^b$, which exists by (2). Moreover, we can choose $z \neq 1$ such that $z \in Z(Q)$, which exists since Q has non-trivial center by (3). Then $Q \subseteq C(z) \subseteq G$, so $|C(z)| = p^c q^b$ where $c \in \{0, \dots, a\}$. By (4), it follows that

$$|\mathcal{C}(z)| = \frac{|G|}{|C(z)|} = \frac{p^a q^b}{p^c q^b} = p^{a-c}.$$

If $c < a$, then G is not simple by Theorem 22.3 since G is non-abelian and $|\mathcal{C}(z)|$ is a conjugacy class with size which is a prime power, contradicting our claim. So $c = a$, which gives $|\mathcal{C}(z)| = 1$. But this means that $C(z) = G$. Moreover, z is central, which gives $\{1\} \neq Z(G) \trianglelefteq G$. Since G is simple, we must have $Z(G) = G$. This would mean that G is abelian, once again contradicting our claim. Therefore, no counterexample exists, so the result holds. \square

23 Galois theory (11/05/2021)

Let F be a field of characteristic 0, and let $p(x) = x^n + a_{n-1}x^{n-1} + \dots + a_1x + a_0 \in F[x]$ be a monic polynomial with roots $\alpha_1, \dots, \alpha_n \in \overline{F}$. Let $K = \{p(\alpha_1, \dots, \alpha_n) : p(x_1, \dots, x_n) \in F[x_1, \dots, x_n]\}$. Notice that K is a subring of \overline{F} , because we may consider the surjective F -algebra homomorphism

$$\begin{aligned} \varphi : F[x_1, \dots, x_n] &\mapsto \overline{F}, \\ p(x_1, \dots, x_n) &\mapsto p(\alpha_1, \dots, \alpha_n), \end{aligned}$$

whose image is K by definition. Note that $\dim_F K < \infty$ since K is spanned by $S = \{\alpha_1^{i_1} \cdots \alpha_n^{i_n} : 0 \leq i_1, \dots, i_n \leq n\}$. To see this, let V be the F -vector subspace of K spanned by S . If $V \subsetneq K$, then there exists a polynomial $p(x_1, \dots, x_n) \in F[x_1, \dots, x_n]$ such that $p(\alpha_1, \dots, \alpha_n) \notin V$. Pick such a p of smallest degree lexicographically; that is, $x_1^{i_1} \cdots x_n^{i_n} <_{\text{lex}} x_1^{j_1} \cdots x_n^{j_n}$ if for some $1 \leq m \leq n$, we have $i_k = j_k$ for all $0 \leq k < m$, and $i_m < j_m$. Note that this is a total ordering.

We claim that all monomials of p have degree less than n . Suppose we had some $x_1^{i_1} \cdots x_s^{i_s} \cdots x_n^{i_n}$ with $i_s \geq n$. Recall that α_s is a root of p , so we have

$$\alpha_s^n + a_{n-1}\alpha_s^{n-1} + \cdots + a_1\alpha_s + a_0 = 0.$$

Rearranging the above equation and multiplying by $\alpha_s^{i_n-n}$ gives

$$\alpha_s^{i_n} = -a_{n-1}\alpha_s^{i_n-1} - \cdots - a_0\alpha_s^{i_n-n}.$$

From this, it follows that

$$\alpha_1^{i_1} \cdots \alpha_s^{i_s} \cdots \alpha_n^{i_n} = -a_{n-1}\alpha_1^{i_1} \cdots \alpha_s^{i_s-1} \cdots \alpha_n^{i_n} - \cdots - a_0\alpha_1^{i_1} \cdots \alpha_s^{i_s-n} \cdots \alpha_n^{i_n}.$$

We can repeat this with all other monomials to reach a contradiction.

Note that K is a field. Indeed, we have $K \subseteq \overline{F}$, so K is an integral domain. Moreover, we showed that $\dim_F K < \infty$. Therefore, if $a \in K \setminus \{0\}$, then the map $L_a : K \rightarrow K$ given by $L_a(x) = ax$ is K -linear and onto. Since L_a is onto, there exists $b \in K$ such that $L_a(b) = 1$, so $ab = ba = 1$. We call K the splitting field of $p(x) = x^n + a_{n-1}x^{n-1} + \cdots + a_1x + a_0 = (x - \alpha_1) \cdots (x - \alpha_n)$. By construction, it is the smallest field extension of F containing all the roots of $p(x) \in F[x]$.

Recall that the Galois group $\text{Gal}(K/F)$ is the set of all F -algebra automorphisms $\sigma : K \rightarrow K$ with $\sigma|_F = \text{id}_F$ together with the operation of composition.

REMARK 23.1

$\text{Gal}(K/F)$ embeds into S_n . To see why, if $\sigma \in \text{Gal}(K/F)$, then σ is uniquely determined by the values $\sigma(\alpha_1), \dots, \sigma(\alpha_n)$. Now, we see that σ permutes $\alpha_1, \dots, \alpha_n$ because if $p(\alpha) = 0$ for some $\alpha \in K$, then

$$\alpha^n + a_{n-1}\alpha^{n-1} + \cdots + a_1\alpha + a_0 = 0.$$

Since σ is F -linear, we obtain

$$\begin{aligned} p(\sigma(\alpha)) &= \sigma(\alpha)^n + a_{n-1}\sigma(\alpha)^{n-1} + \cdots + a_1\sigma(\alpha) + a_0 \\ &= \sigma(\alpha^n + a_{n-1}\alpha^{n-1} + \cdots + a_1\alpha + a_0) \\ &= \sigma(0) = 0. \end{aligned}$$

Now, let $G = \text{Gal}(K/F)$. The fundamental theorem of Galois theory tells us that if we are given a subgroup $\{\text{id}\} \subseteq H \subseteq G$, then $K^H = \{a \in K : \tau(a) = a \text{ for all } \tau \in H\}$ forms a field, and the converse is also true. Moreover, we have $H_1 \subseteq H_2$ if and only if $K^{H_1} \supseteq K^{H_2}$; that is, this correspondence is inclusion-reversing. In particular, notice that $K^G = \{a \in K : \sigma(a) = a \text{ for all } \sigma \in \text{Gal}(K/F)\} = F$.

THEOREM 23.2: KRONECKER

Consider the polynomial

$$p(x) = x^n + a_{n-1}x^{n-1} + \cdots + a_1x + a_0 = (x - \alpha_1) \cdots (x - \alpha_n) \in \mathbb{Z}[x].$$

If $|\alpha_i| \leq 1$ for all $i = 1, \dots, n$, then each α_i is either 0 or a root of unity.

PROOF. First, note that $\alpha_1, \dots, \alpha_n \in \mathbb{A}$. Let K be the splitting field of $p(x) \in F[x]$, and let $G = \text{Gal}(K/\mathbb{Q})$. For $j \in \mathbb{Z}^+$, define the polynomial

$$p_j(x) = (x - \alpha_1^j) \cdots (x - \alpha_n^j).$$

Note that $p_j(x) \in \mathbb{Q}[x]$. Indeed, if $\sigma \in \text{Gal}(K/\mathbb{Q})$, then by K -linearity, we obtain

$$\sigma(p_j(x)) = \sigma((x - \alpha_1^j) \cdots (x - \alpha_n^j)) = (x - \sigma(\alpha_1^j)) \cdots (x - \sigma(\alpha_n^j)) = p_j(x).$$

This holds for all $\sigma \in \text{Gal}(K/\mathbb{Q})$. The coefficients of $p_j(x)$ are all in $K^G = \mathbb{Q}$ (where this equality holds by the fundamental theorem of Galois theory). It follows that $p_j(x) \in \mathbb{Z}[x]$ since $\alpha_1, \dots, \alpha_n \in \mathbb{A}$, and so the coefficients are in $\mathbb{A} \cap \mathbb{Q} = \mathbb{Z}$.

Now, write

$$p_j(x) = x^n + a_{n-1,j}x^{n-1} + \cdots + a_{1,j}x + a_{0,j} \in \mathbb{Z}[x].$$

We claim that $|a_{n-k,j}| \leq \binom{n}{k}$. Indeed, by expanding out our original definition of $p_j(x)$, we have

$$p_j(x) = x^n - (\alpha_1^j + \cdots + \alpha_n^j)x^{n-1} + \cdots + (-1)^k \left(\sum_{1 \leq i_1 < \cdots < i_k \leq n} \alpha_{i_1}^j \cdots \alpha_{i_k}^j \right) x^{n-k} + \cdots.$$

Then we have

$$a_{n-k,j} = (-1)^k \sum_{1 \leq i_1 < \cdots < i_k \leq n} \alpha_{i_1}^j \cdots \alpha_{i_k}^j,$$

and since $|\alpha_i| \leq 1$ for all $i = 1, \dots, n$, it follows that $|a_{n-k,j}| \leq \binom{n}{k}$. Now, observe that the set $X = \{x^n + a_{n-1}x^{n-1} + \cdots + a_1x + a_0 \in \mathbb{Z}[x] : |a_i| \leq \binom{n}{i} \text{ for all } i = 0, \dots, n-1\}$ is finite, and $p_j(x) \in X$ for all $j \in \mathbb{Z}^+$. In particular, there exist integers $m_1 < m_2$ such that $p_{m_1}(x) = p_{m_2}(x)$. Notice that this implies that $\{\alpha_1^{m_1}, \dots, \alpha_n^{m_1}\} = \{\alpha_1^{m_2}, \dots, \alpha_n^{m_2}\}$. Then we either have $\alpha_i = 0$ or $\alpha_i^{m_2 - m_1} = 1$ for each $i = 1, \dots, n$, completing the proof. \square

24 Lemma for Burnside's theorem, tensor products (11/08/2021)

Now that we are equipped with Kronecker's theorem, we can prove the following lemma we used towards proving Burnside's theorem. In the interest of time, we will prove a slightly weaker version of it.

LEMMA 24.1

Let G be a non-abelian simple group. Let χ be an irreducible character of degree $n \geq 2$. If $g \in G$ with $g \neq 1$ and $\chi(g)/n \in \mathbb{A}$, then $\chi(g) = 0$.

PROOF. Note that there exists an integer d such that $g^d = 1$. If χ is the character of some representation $\rho : G \rightarrow \text{GL}_n(\mathbb{C})$, then

$$\rho(g) \sim \begin{pmatrix} \omega_1 & & 0 \\ & \ddots & \\ 0 & & \omega_n \end{pmatrix},$$

where $\omega_1, \dots, \omega_n$ are d -th roots of unity. Indeed, every matrix over \mathbb{C} is triangularizable. But $g^d = 1$ implies that $\rho(g)^d - I = 0$, so the minimal polynomial of $\rho(g)$ divides $x^d - 1$, and the roots of $x^d - 1$ are distinct. A matrix over an algebraically closed field is diagonalizable if and only if its minimal polynomial has distinct roots, so in particular, $\rho(g)$ is diagonalizable. Now, observe that

$$\frac{\chi(g)}{n} = \frac{\omega_1 + \cdots + \omega_n}{n}.$$

By the Cauchy-Schwarz inequality, we see that

$$\left| \frac{\chi(g)}{n} \right| = \left\langle (\omega_1, \dots, \omega_n), \left(\frac{1}{n}, \dots, \frac{1}{n} \right) \right\rangle \leq \sqrt{n} \cdot \sqrt{\frac{1}{n}} = 1,$$

with equality if and only if $\omega_1 = \dots = \omega_n$. We now consider two cases.

If $\omega_1 = \dots = \omega_n =: \omega$, then

$$\rho(g) \sim \begin{pmatrix} \omega & & 0 \\ & \ddots & \\ 0 & & \omega \end{pmatrix} = \omega I.$$

Note that ωI commutes with everything in $\text{GL}_n(\mathbb{C})$. Hence, we obtain $\rho(ghg^{-1}h^{-1}) = \rho(g)\rho(h)\rho(g)^{-1}\rho(h)^{-1} = I$ for all $h \in G$. This means that $ghg^{-1}h^{-1} \in \ker \rho$ for all $h \in G$. Note that $\ker \rho \trianglelefteq G$, and since G is simple, we either have $\ker \rho = G$ or $\ker \rho = \{1\}$. The first case is impossible since ρ is irreducible of degree $n \geq 2$. Then $\ker \rho = \{1\}$, so $ghg^{-1}h^{-1} = 1$ for all $h \in G$. This implies that $g \in Z(G) \trianglelefteq G$. But we assumed that $g \neq 1$, so G being simple shows that $Z(G) = G$. This is a contradiction since G is non-abelian.

Assume now that $\omega_1, \dots, \omega_n$ are not all equal. In this case, we have

$$\left| \frac{\chi(g)}{n} \right| = \left| \frac{\omega_1 + \dots + \omega_n}{n} \right| < 1.$$

Let $\alpha = \chi(g)/n$, and let $K = \mathbb{Q}(e^{2\pi i/d})$. Notice that $\omega_1, \dots, \omega_n \in K$ as they are all d -th roots of unity. A \mathbb{Q} -algebra automorphism sends d -th roots of unity to other d -th roots of unity, since $\omega^d = 1$ implies that $\sigma(\omega)^d = \sigma(\omega^d) = \sigma(1) = 1$. Now, if $\sigma \in \text{Gal}(K/\mathbb{Q})$, then σ is \mathbb{Q} -linear, so we get

$$\sigma(\alpha) = \frac{\sigma(\omega_1) + \dots + \sigma(\omega_n)}{n}.$$

Moreover, $\sigma(\omega_1), \dots, \sigma(\omega_n)$ are not all the same since σ is an automorphism, and hence injective. Therefore, we have $|\sigma(\alpha)| < 1$ for all $\sigma \in \text{Gal}(K/\mathbb{Q})$.

Assume that $\alpha \in \mathbb{A}$, so $\sigma(\alpha) \in \mathbb{A}$ for all $\sigma \in \text{Gal}(K/\mathbb{Q})$. Note that the polynomial

$$\prod_{\sigma \in \text{Gal}(K/\mathbb{Q})} (x - \sigma(\alpha))$$

lives in $\mathbb{Q}[x] \cap \mathbb{A}[x] = \mathbb{Z}[x]$. Note that α is a root of this polynomial with $|\alpha| < 1$. By Kronecker, α is either 0 or a root of unity, with the latter case being impossible since $|\alpha| \neq 1$. It follows that $\alpha = |\chi(g)|/n$ must be 0, and hence $\chi(g) = 0$. \square

We now introduce tensor products. Let R be a ring, let $M = M_R$ be a right R -module, and let $N = {}_R N$ be a left R -module. We can form the tensor product $M \otimes_R N$ of M and N .

Given an abelian group A , we say that a map $f : M \times N \rightarrow A$ is **bilinear** if

- (i) $f(m_1 + m_2, n) = f(m_1, n) + f(m_2, n)$ for all $m_1, m_2 \in M$, $n \in N$, and $a \in \mathbb{Z}$;
- (ii) $f(m, n_1 + n_2) = f(m, n_1) + f(m, n_2)$ for all $m \in M$, $n_1, n_2 \in N$, and $a \in \mathbb{Z}$;
- (iii) $f(m \cdot r, n) = f(m, r \cdot n)$ for all $m \in M$, $n \in N$, and $r \in R$.

We can think of bilinear maps as an abstraction of multiplication between modules.

REMARK 24.2

Note that we need the left and right pairing of the modules to make this work in general. Suppose that M and R are both right R -modules. We would like to impose that $f(m \cdot r, n) = f(m, n \cdot r)$ for all $m \in M$, $n \in N$, and $r \in R$. But this means that for all $r, s \in R$, we have $f(m(rs), n) = f(m, n(rs))$, and also

$$f(m(rs), n) = f(mr, ns) = f(m, n(sr)).$$

In particular, we require that $f(m, n(rs - sr)) = 0$ for all $m \in M$, $n \in N$, and $r, s \in R$. This is not an issue for commutative rings, but there are rings R such that $1 \in [R, R]$, in which case the only bilinear map is the zero map. The same issue occurs with two left R -modules.

We now formally define tensor products.

DEFINITION 24.3

Let T be the free abelian group on generators $e_{(m,n)}$ where $(m,n) \in M \times N$. That is, we have

$$T = \bigoplus_{(m,n) \in M \times N} \mathbb{Z}e_{(m,n)}.$$

Let $U \subseteq T$ be the \mathbb{Z} -submodule spanned by the relations

- (i) $e_{(m_1+m_2, n)} - e_{(m_1, n)} - ae_{(m_2, n)}$;
- (ii) $e_{(m, n_1+an_2)} - e_{(m, n_1)} - ae_{(m, n_2)}$; and
- (iii) $e_{(mr, n)} - e_{(m, rn)}$.

where $m, m_1, m_2 \in M$, $n, n_1, n_2 \in N$, $a \in \mathbb{Z}$ and $r \in R$. Then the **tensor product** of M and N is defined to be $M \otimes_R N := T/U$.

25 Universal property, uniqueness of tensor products (11/10/2021)

Let R be a ring, let $M = M_R$ be a right R -module, and let $N = {}_R N$ a left R -module. Then $M \otimes_R N = T/U$ is an abelian group, with T and U as in the above definition. We write $m \otimes n$ to mean the coset $e_{(m,n)} + U$ in $M \otimes_R N$.

REMARK 25.1

Not every element in $M \otimes_R N$ can be expressed in the form $m \otimes n$ in general, but every element is a \mathbb{Z} -linear combination of elements of the form $m \otimes n$.

We have a map

$$\begin{aligned} \pi : M \times N &\rightarrow M \otimes_R N \\ (m, n) &\mapsto m \otimes n \end{aligned}$$

which is bilinear and hence satisfies the property

$$\pi(m_1 + m_2, n) = (m_1 + m_2) \otimes n = m_1 \otimes n + m_2 \otimes n.$$

This is the case since $e_{(m_1+m_2,n)} \equiv e_{(m_1,n)} + e_{(m_2,n)} \pmod{U}$. Moreover, $e_{(mr,n)} \equiv e_{(m,rn)} \pmod{U}$, so $mr \otimes n = m \otimes rn$. We now consider the universal property of tensor products.

PROPOSITION 25.2: UNIVERSAL PROPERTY OF TENSOR PRODUCTS

If A is an abelian group and $\theta : M \times N \rightarrow A$ is a bilinear map, then there exists a unique group homomorphism $\hat{\theta} : M \otimes_R N \rightarrow A$.

$$\begin{array}{ccc} M \times N & \xrightarrow{\theta} & A \\ \downarrow \pi & \nearrow \hat{\theta} & \\ M \otimes_R N & & \end{array}$$

PROOF. Given a bilinear map $\theta : M \times N \rightarrow A$, define $\hat{\theta} : T \rightarrow A$ by

$$\hat{\theta}(e_{(m,n)}) = \theta(m, n).$$

This extends uniquely to a group homomorphism since the elements $e_{(m,n)}$ generate T . We claim that $U \subseteq \ker \hat{\theta}$. To see this, it suffices to show that

$$(i) \quad \hat{\theta}(e_{(m_1+m_2,n)} - e_{(m_1,n)} - ae_{(m_2,n)}) = 0;$$

$$(ii) \quad \hat{\theta}(e_{(m,n_1+an_2)} - e_{(m,n_1)} - ae_{(m,n_2)}) = 0;$$

$$(iii) \quad \hat{\theta}(e_{(mr,n)} - e_{(m,rn)}) = 0.$$

We check (iii), and we leave (i) and (ii) as exercises. We have

$$\hat{\theta}(e_{(mr,n)} - e_{(m,rn)}) = \theta(mr, n) - \theta(m, rn) = 0,$$

since θ is bilinear. Now, using the map $\psi : M \times N \rightarrow T$ given by

$$\psi(m, n) \mapsto e_{(m,n)},$$

the map $\hat{\theta} : T \rightarrow A$ is unique. Since U is in $\ker \hat{\theta}$, we have $\hat{\theta}(t + u) = \hat{\theta}(t)$ for all $u \in U$. This allows us to extend $\hat{\theta}$ uniquely to a map $\tilde{\theta}$ on the cosets; that is, we have a map from $T/U = M \otimes_R N$ to A . Letting $\psi' : T \rightarrow T/U$ be the canonical projection, we obtain the following diagram.

$$\begin{array}{ccc} M \times N & \xrightarrow{\theta} & A \\ \downarrow \psi & \nearrow \hat{\theta} & \\ T & & \\ \downarrow \psi' & \nearrow \tilde{\theta} & \\ T/U & & \end{array}$$

Setting $\pi = \psi' \circ \psi$ will give us the diagram above, completing the proof. \square

PROPOSITION 25.3: UNIQUENESS OF TENSOR PRODUCTS

We have the bilinear map

$$\begin{aligned}\pi : M \times N &\rightarrow M \otimes_R N \\ (m, n) &\mapsto m \otimes n\end{aligned}$$

which satisfies the universal property. Suppose that Ω is another abelian group with a bilinear map $\pi' : M \times N \rightarrow \Omega$ which also has the universal property. Then $M \otimes_R N \cong \Omega$.

PROOF. By the universal property of Ω , there exists a unique group homomorphism $\tilde{\pi}' : M \otimes_R N \rightarrow \Omega$ with $\tilde{\pi}' \circ \pi = \pi'$. Similarly, by the universal property of $M \otimes_R N$, there is a unique group homomorphism $\tilde{\pi} : \Omega \rightarrow M \otimes_R N$ with $\tilde{\pi} \circ \pi' = \pi$.

$$\begin{array}{ccc} M \times N & \xrightarrow{\pi'} & \Omega \\ \pi \downarrow & \nearrow \tilde{\pi}' & \\ M \otimes_R N & & \end{array} \quad \begin{array}{ccc} M \times N & \xrightarrow{\pi} & M \otimes_R N \\ \pi' \downarrow & \nearrow \tilde{\pi} & \\ \Omega & & \end{array}$$

Clearly, there is a unique map $\text{id} : \Omega \rightarrow \Omega$. Using the maps $\tilde{\pi} : \Omega \rightarrow M \otimes_R N$ and $\tilde{\pi}' : M \otimes_R N \rightarrow \Omega$, we obtain the following diagram.

$$\begin{array}{ccc} M \times N & \xrightarrow{\pi'} & \Omega \\ \pi' \downarrow & \nearrow \text{id} & \uparrow \tilde{\pi}' \\ \Omega & \xrightarrow{\tilde{\pi}} & M \otimes_R N \end{array}$$

Notice that

$$(\tilde{\pi}' \circ \tilde{\pi}) \circ \pi' = \tilde{\pi}' \circ (\tilde{\pi} \circ \pi') = \tilde{\pi}' \circ \pi = \pi'.$$

Therefore, we get the following diagram.

$$\begin{array}{ccc} M \times N & \xrightarrow{\pi'} & \Omega \\ \pi' \downarrow & \nearrow \tilde{\pi}' \circ \tilde{\pi} & \\ \Omega & & \end{array}$$

But the map $\Omega \rightarrow \Omega$ is unique by the universal property, and so we must have $\tilde{\pi}' \circ \tilde{\pi} = \text{id}_\Omega$. By an analogous argument, we find that $\tilde{\pi} \circ \tilde{\pi}' = \text{id}_{M \otimes_R N}$. This means that $\tilde{\pi} : \Omega \rightarrow M \otimes_R N$ and $\tilde{\pi}' : M \otimes_R N \rightarrow \Omega$ are inverses. In particular, it follows that these maps are isomorphisms. \square

EXAMPLE 25.4

Let $R = \mathbb{Z}$, $M = \mathbb{Q}$, and $N = \mathbb{Z}/3\mathbb{Z}$. Note that $\mathbb{Q} \otimes_{\mathbb{Z}} \mathbb{Z}/3\mathbb{Z} = (0)$. Indeed, in this case, we have

$$T = \bigoplus_{(a,b) \in \mathbb{Q} \times \mathbb{Z}/3\mathbb{Z}} \mathbb{Z}e_{(a,b)}.$$

Consider $a \otimes [1]_3$. We have

$$a \otimes [1]_3 = \frac{a}{3} \cdot 3 \otimes [1]_3 = \frac{a}{3} \otimes 3 \cdot [1]_3 = \frac{a}{3} \otimes 0 = \frac{a}{3} \otimes 0 \cdot 0 = 0 \otimes 0 = 0.$$

To see that $0 \otimes 0 = 0$, note that by bilinearity, we have $0 \otimes 0 = (0 + 0) \otimes 0 = 0 \otimes 0 + 0 \otimes 0$. Subtracting both sides by $0 \otimes 0$ gives the result. Notice that there is nothing special about 1 here; we could take $[0]_3$ and $[2]_3$ as well. In general, tensoring an abelian group with \mathbb{Q} kills the torsion.

EXAMPLE 25.5

Let $m, n \in \mathbb{Z}^+$. Let $d = \gcd(m, n)$. We claim that $\mathbb{Z}/m\mathbb{Z} \otimes_{\mathbb{Z}} \mathbb{Z}/n\mathbb{Z} = \mathbb{Z}/d\mathbb{Z}$. We have

$$[i]_m \otimes [j]_n = [i]_m \otimes j \cdot [1]_n = [ij]_m \otimes [1]_n.$$

For $a \in \mathbb{Z}$, we can write $a = u + ms + nt$ where $u \in \{0, 1, \dots, d-1\}$. This gives

$$\begin{aligned} [ij]_m \otimes [1]_n &= [u + ms + nt]_m \otimes [1]_n \\ &= [u + nt]_m \otimes [1]_n \\ &= ([u]_m + [t]_m \cdot n) \otimes [1]_n \\ &= [u]_m \otimes [1]_n + [t]_m \cdot n \otimes [1]_n \\ &= u \cdot [1]_m \otimes [1]_n. \end{aligned}$$

Hence, we have $|\mathbb{Z}/m\mathbb{Z} \otimes_{\mathbb{Z}} \mathbb{Z}/n\mathbb{Z}| \leq d$ since $u \in \{0, 1, \dots, d-1\}$. Notice we can define a multiplication via

$$\begin{aligned} \theta : \mathbb{Z}/m\mathbb{Z} \times \mathbb{Z}/n\mathbb{Z} &\rightarrow \mathbb{Z}/d\mathbb{Z} \\ ([a]_m, [b]_n) &\mapsto [ab]_d, \end{aligned}$$

and this map is onto. Using the universal property, we have a map $\tilde{\theta} : \mathbb{Z}/m\mathbb{Z} \otimes_{\mathbb{Z}} \mathbb{Z}/n\mathbb{Z} \rightarrow \mathbb{Z}/d\mathbb{Z}$ which is onto, and $\tilde{\theta}$ is an isomorphism.

$$\begin{array}{ccc} \mathbb{Z}/m\mathbb{Z} \times \mathbb{Z}/n\mathbb{Z} & \xrightarrow{\theta} & \mathbb{Z}/d\mathbb{Z} \\ \downarrow \pi & \nearrow \tilde{\theta} & \\ \mathbb{Z}/m\mathbb{Z} \otimes_{\mathbb{Z}} \mathbb{Z}/n\mathbb{Z} & & \end{array}$$

REMARK 25.6

Let S and R be rings. If $M = {}_S M_R$ (that is, M is a left S -module and right R -module, and we call M a (S, R) -bimodule) and $N = {}_R N$, then $M \otimes_R N$ is a left S -module via the action $s \cdot (m \otimes n) = (s \cdot m) \otimes n$.

Similarly, if S' is another ring and $N = {}_R M_{S'}$ is an (R, S') -bimodule, then $M \otimes_R N$ is a right S' -module via the action $(m \otimes n) \cdot s' = m \otimes (n \cdot s')$.

26 More on tensor products, induced representations (11/12/2021)

We first make the small remark that every ring R is a \mathbb{Z} -algebra, as there is always a ring homomorphism $\mathbb{Z} \rightarrow R$. Now, we'll cover another example of a tensor product.

EXAMPLE 26.1

Let k be a field. Let V and W be k -vector spaces with bases $\{v_\alpha\}_{\alpha \in X}$ and $\{w_\beta\}_{\beta \in Y}$ respectively. Then $V \otimes_k W$ is a k -vector space with basis $\{v_\alpha \otimes w_\beta\}_{(\alpha, \beta) \in X \times Y}$.

PROOF. We can think of V as a (k, k) -bimodule with $\lambda \cdot v = v \cdot \lambda$. Then $V \otimes_k W$ is a k -vector space by Remark 25.6. Notice that $V \otimes_k W$ is spanned by elements of the form $v \otimes w$ with $v \in V$ and $w \in W$. Writing $v = \sum_{\alpha \in X} c_\alpha v_\alpha$ and $w = \sum_{\beta \in Y} d_\beta w_\beta$, we have

$$\begin{aligned} v \otimes w &= \sum_{\alpha \in X} c_\alpha v_\alpha \otimes w \\ &= \sum_{\alpha \in X} c_\alpha \cdot (v_\alpha \otimes w) \\ &= \sum_{\alpha \in X} c_\alpha v_\alpha \otimes \sum_{\beta \in Y} d_\beta w_\beta \\ &= \sum_{\alpha \in X} \sum_{\beta \in Y} c_\alpha v_\alpha \otimes (d_\beta w_\beta) \\ &= \sum_{\alpha \in X} \sum_{\beta \in Y} c_\alpha d_\beta (v_\alpha \otimes w_\beta). \end{aligned}$$

To show linear independence, let U be the k -vector space with basis $\{e_{(\alpha, \beta)} : (\alpha, \beta) \in X \times Y\}$. Define the map $\phi : V \times W \rightarrow U$ by the rule

$$\phi \left(\sum_{\alpha \in X} c_\alpha v_\alpha, \sum_{\beta \in Y} d_\beta w_\beta \right) = \sum_{\alpha \in X} \sum_{\beta \in Y} c_\alpha d_\beta e_{(\alpha, \beta)}.$$

We see that ϕ is bilinear by construction. In particular, note that $\phi(\lambda v, w) = \lambda \cdot \phi(v, w)$. Moreover, we know that $\lambda(v \otimes w) = \lambda v \otimes w$. By the universal property, there exists a unique map $\tilde{\phi} : V \otimes_k W \rightarrow U$ which makes the following diagram commute.

$$\begin{array}{ccc} V \times W & \xrightarrow{\phi} & U \\ \pi \downarrow & \nearrow \tilde{\phi} & \\ V \otimes_k W & & \end{array}$$

In fact, notice that $\tilde{\phi}$ is k -linear. Now, we have

$$\tilde{\phi}(v_\alpha \otimes w_\beta) = \tilde{\phi} \circ \pi(v_\alpha, w_\beta) = \phi(v_\alpha, w_\beta) = e_{(\alpha, \beta)}.$$

Suppose that we have $\sum c_{\alpha, \beta} v_\alpha \otimes w_\beta = 0$. Then we obtain

$$0 = \tilde{\phi} \left(\sum c_{\alpha, \beta} v_\alpha \otimes w_\beta \right) = \sum c_{\alpha, \beta} \tilde{\phi}(v_\alpha \otimes w_\beta) = \sum c_{\alpha, \beta} e_{(\alpha, \beta)},$$

and hence $c_{\alpha, \beta} = 0$ for all $(\alpha, \beta) \in X \times Y$. Therefore, $\{v_\alpha \otimes w_\beta\}_{(\alpha, \beta) \in X \times Y}$ forms a basis for $V \otimes_k W$. \square

Let R be a ring, let $M = M_R$ be a right R -module, and let $N = {}_R N$ be a left R -module. By Exercise (iii) in Assignment 5, we have $R_R \otimes_R N \cong N$ (as left R -modules) and $M \otimes_R R_R \cong M$ (as right R -modules). This can be shown by considering the bilinear maps $(r, n) \mapsto rn$ and $(m, r) \mapsto mr$, and showing that the universal property holds.

EXERCISE 26.2

Let R be a ring. Let (M_α) be a family of left R -modules, and N be a right R -module. Show that

$$\left(\bigoplus_{\alpha} M_{\alpha} \right) \otimes_R N \cong \bigoplus_{\alpha} (M_{\alpha} \otimes_R N).$$

Similarly, if (N_β) is a family of right R -modules and M is a left R -module, then show that

$$M \otimes_R \left(\bigoplus_{\beta} N_{\beta} \right) \cong \bigoplus_{\beta} (M \otimes_R N_{\beta}).$$

Hint: Show that these have the universal property.

Intuitively, this makes sense because we can think of a tensor product as multiplication, and we have a direct sum of modules. We would expect multiplication to distribute over the sum.

COROLLARY 26.3

Let k be a field. If V and W are k -vector spaces with bases $\{v_\alpha\}_{\alpha \in X}$ and $\{w_\beta\}_{\beta \in Y}$ respectively, then

$$V \otimes_k W \cong \bigoplus k v_\alpha \otimes w_\beta.$$

PROOF. Since $\{v_\alpha\}_{\alpha \in X}$ and $\{w_\beta\}_{\beta \in Y}$ are bases for V and W respectively, we can write $V \cong \bigoplus_{\alpha \in X} k v_\alpha$ and $W \cong \bigoplus_{\beta \in Y} k w_\beta$. Using Exercise 26.2, it follows that

$$\begin{aligned} V \otimes_k W &\cong \left(\bigoplus_{\alpha \in X} k v_\alpha \right) \otimes_k W \\ &\cong \bigoplus_{\alpha \in X} k v_\alpha \otimes_k W \\ &\cong \bigoplus_{\alpha \in X} (k v_\alpha) \otimes \left(\bigoplus_{\beta \in Y} k w_\beta \right) \\ &\cong \bigoplus_{\alpha \in X} \bigoplus_{\beta \in Y} k v_\alpha \otimes k w_\beta \\ &\cong \bigoplus_{\alpha \in X} \bigoplus_{\beta \in Y} k v_\alpha \otimes w_\beta. \end{aligned}$$

□

We now begin induced representations. Suppose we are given a subgroup $H \leq G$, and a representation W of H (that is, W is a left $k[H]$ -module). Then we can find a representation $W \uparrow_H^G$ of G (that is, a left $k[G]$ -module), called the **induced representation** of W up to G . Let's see how this is done.

Since H is a subgroup of G , we see that $k[H]$ is a subring of $k[G]$. We can think of $k[G]$ as a $(k[G], k[G])$ -bimodule. In particular, we can view $k[G]$ as a left $k[G]$ -module, and a right $k[H]$ -module, forgetting the fact

that it is a right $k[G]$ -module. Then we can form a $k[G]$ -module from W by

$$W \uparrow_H^G := k[G] \otimes_{k[H]} W.$$

Notice that this tensor product makes sense because $k[G]$ is a right $k[H]$ -module, and W is a left $k[H]$ -module.

Recall that $k[G]$ is a free right $k[H]$ -module with basis x_1, \dots, x_m , where $G = x_1H \cup x_2H \cup \dots \cup x_mH$, where the union is disjoint so that each x_i is a left coset representative. Indeed, we can write

$$\sum_{g \in G} \alpha_g g = \sum_{h \in H} \alpha_{x_1 h} (x_1 h) + \dots + \sum_{h \in H} \alpha_{x_m h} (x_m h),$$

so every element in $k[G]$ decomposes uniquely in the form

$$\sum_{g \in G} \alpha_g g = x_1 \sum_{h \in H} \alpha_{x_1 h} h + \dots + x_m \sum_{h \in H} \alpha_{x_m h} h.$$

Since each $\sum_{h \in H} \alpha_{x_i h} h \in k[H]$, we get

$$k[G] \cong x_1 k[H] \oplus \dots \oplus x_m k[H].$$

Now, it follows that

$$\begin{aligned} k[G] \otimes_{k[H]} W &\cong (x_1 k[H] \oplus \dots \oplus x_m k[H]) \otimes_{k[H]} W \\ &\cong (x_1 k[H] \otimes_{k[H]} W) \oplus \dots \oplus (x_m k[H] \otimes_{k[H]} W). \end{aligned}$$

By Exercise (iii) in Assignment 5, we have $k[H] \otimes_{k[H]} W \cong W$. Hence, we obtain

$$k[G] \otimes_{k[H]} W \cong x_1 W \oplus \dots \oplus x_m W.$$

More precisely, if $\{w_1, \dots, w_p\}$ is a basis for W , then $W \uparrow_H^G$ is the k -span of $\{x_i \otimes w_j : 1 \leq i \leq m, 1 \leq j \leq p\}$. Notice that each $x_i W$ is p -dimensional, so $W \uparrow_H^G$ is mp -dimensional. Now, how does $g \in G$ act on this basis? First, note that $g \cdot (x_i \otimes w) = (g \cdot x_i) \otimes w$ by bilinearity. Once again, we recall that $G = x_1 H \cup \dots \cup x_m H$, so there exists a unique $j \in \{1, \dots, m\}$ and $h \in H$ such that $g \cdot x_i = x_j \cdot h$. We can take

$$g \cdot (x_i \otimes w) = (g \cdot x_i) \otimes w = (x_j \cdot h) \otimes w = x_j \otimes h \cdot w$$

to be our action. Since W is a representation of H , we have a homomorphism $\rho : H \rightarrow \text{GL}(W)$. In particular, $\rho(h)$ looks like an $m \times m$ block matrix with copies of $\rho(h)$ or the zero matrix in the blocks.

EXAMPLE 26.4

Let $k = \mathbb{C}$. Let $G = S_3$, and let $H = A_3 = \{\text{id}, (123), (132)\}$ be the subgroup of index 3. Notice that $S_3 = \text{id} \cdot H \cup (12) \cdot H$, so we can take $x_1 = \text{id}$ and $x_2 = (12)$ to be our coset representatives. Take $W = \mathbb{C}$ to be our H -module, with action given by $\text{id} \cdot 1 = 1$, $(123) \cdot 1 = e^{2\pi i/3}$, and $(132) \cdot 1 = e^{4\pi i/3}$.

Now, the basis of $W \uparrow_H^{S_3}$ is simply given by $\{x_1 \otimes 1, x_2 \otimes 1\}$, since $\{1\}$ forms a basis for $W = \mathbb{C}$. Write $v_1 = x_1 \otimes 1$ and $v_2 = x_2 \otimes 1$. Let's see how the elements of S_3 act on $W \uparrow_H^{S_3}$.

We first consider (12) . Notice that

$$(12) \cdot v_1 = (12) \cdot (x_1 \otimes 1) = ((12) \cdot x_1) \otimes 1 = x_2 \otimes 1 = 0 \cdot v_1 + 1 \cdot v_2.$$

Similarly, we find that

$$(12) \cdot v_2 = (12) \cdot (x_2 \otimes 1) = ((12) \cdot x_2) \otimes 1 = x_1 \otimes 1 = 1 \cdot v_1 + 0 \cdot v_2.$$

Therefore, we have

$$\rho((12)) = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}.$$

What about the action of (123) ? Notice that $(123) \cdot v_1 = (123) \cdot (x_1 \otimes 1) = (123) \cdot x_1 \otimes 1$, and since $(123) \in H$, we can move it to the other side. This becomes

$$x_1 \otimes ((123) \cdot 1) = x_1 \otimes e^{2\pi i/3} = e^{2\pi i/3}(x_1 \otimes 1) = e^{2\pi i/3} \cdot v_1 + 0 \cdot v_2.$$

On the other hand, we have $(123) \cdot v_2 = (123) \cdot (x_2 \otimes 1) = (123) \cdot (12) \otimes 1 = (12) \cdot (132) \otimes 1$. Notice that $(132) \in H$, so we can move it to the other side to obtain

$$(12) \otimes ((132) \cdot 1) = (12) \otimes e^{4\pi i/3} = e^{4\pi i/3}(x_2 \otimes 1) = 0 \cdot v_1 + e^{4\pi i/3} \cdot v_2.$$

Therefore, we obtain

$$\rho((123)) = \begin{pmatrix} e^{2\pi i/3} & 0 \\ 0 & e^{4\pi i/3} \end{pmatrix}.$$

Now that we have the matrices for (12) and (123) , we can compute the rest by multiplying, since these elements generate S_3 .

Note that ρ is an irreducible 2-dimensional representation of S_3 . It is clear that it is 2-dimensional. Notice that if χ is the character of ρ , then $\chi((12)) = 0$ by construction, $\chi((123)) = e^{2\pi i/3} + e^{4\pi i/3} = -1$, and $\chi(\text{id}) = 2$. Since χ is a class function, it is now completely determined. Computing the inner product of χ with itself, we have

$$\langle \chi, \chi \rangle = \frac{1}{6}(2^2 \cdot 1 + 0^2 \cdot 3 + (-1)^2 \cdot 2) = 1,$$

so ρ is in fact irreducible. These values also check out with the character table of S_3 that we computed in Example 16.2!

27 Induced characters and transitivity (11/15/2021)

Let k be a field, and let H be a subgroup of G . Then G is the union of disjoint cosets $x_1 H \cup \cdots \cup x_m H$. If W is a left $k[H]$ -module with k -basis $\{w_1, \dots, w_p\}$, then we obtain a representation

$$\rho : H \rightarrow \text{GL}_p(k) \cong \text{GL}(W)$$

which can be written in matrix form as $\rho(h) = (\rho_{ij}(h))_{1 \leq i, j \leq p}$ with action

$$h \cdot w_j = \sum_{i=1}^p \rho_{ij}(h) \cdot w_i.$$

Recall that the induced representation of W up to G is a left $k[G]$ -module given by $W \uparrow_H^G = k[G] \otimes_{k[H]} W$. This has basis $\{x_i \otimes w_j : 1 \leq i \leq m, 1 \leq j \leq p\}$. Note that $g \cdot x_i \in x_q H$ for some $q \in \{1, \dots, m\}$, so we can take the action

$$g \cdot (x_i \otimes w) = x_q \otimes (h \cdot w).$$

With this basis, we get a representation

$$\rho \uparrow_H^G : G \rightarrow \text{GL}_{mp}(k).$$

What is $\rho \uparrow_H^G(g)$? If we treat each $\{x_j \otimes w_1, \dots, x_j \otimes w_p\}$ as a “block”, we obtain

$$\begin{aligned} g \cdot (x_j \otimes w_1) &= x_q \otimes (h \cdot w_1) = x_q \otimes [\rho_{11}(h)w_1 + \cdots + \rho_{p1}(h)w_p] \\ &\vdots \\ g \cdot (x_j \otimes w_p) &= x_q \otimes (h \cdot w_p) = x_q \otimes [\rho_{1p}(h)w_1 + \cdots + \rho_{pp}(h)w_p]. \end{aligned}$$

Then the j -th column in the block matrix $\rho \uparrow_H^G(g)$ has $\rho(h)$ in the q -th row, and 0 in the other rows. This gives us an $m \times m$ block matrix from $\rho(h)$, where the blocks are $p \times p$ matrices, and the (i, j) -th block is 0 if $gx_j \in x_i H$, and it is $\rho(x_i^{-1}gx_j)$ if $gx_j \notin x_i H$ (since $gx_j = x_i h$ implies that $h = x_i^{-1}gx_j$).

Now, what is the character $\chi \uparrow_H^G = \text{Tr}(\rho \uparrow_H^G)$? If we write

$$\rho \uparrow_H^G(g) = \begin{pmatrix} A_{11} & \cdots & A_{1m} \\ \vdots & \ddots & \vdots \\ A_{m1} & \cdots & A_{mm} \end{pmatrix}$$

where each A_{ij} is a $p \times p$ matrix, we get

$$\chi \uparrow_H^G(g) = \text{Tr}(A_{11}) + \text{Tr}(A_{22}) + \cdots + \text{Tr}(A_{mm}).$$

Notice that $A_{ii} \neq 0$ when $gx_i \in x_i H$, or equivalently, $x_i^{-1}gx_i \in H$. In this case, we have $A_{ii} = \rho(x_i^{-1}gx_i)$. So if $\chi = \text{Tr}(\rho)$, then we get

$$\chi \uparrow_H^G(g) = \sum_{\{i : x_i^{-1}gx_i \in H\}} \text{Tr}(\rho(x_i^{-1}gx_i)) = \sum_{\{i : x_i^{-1}gx_i \in H\}} \chi(x_i^{-1}gx_i).$$

EXERCISE 27.1

Show that we have the equivalent formula

$$\chi \uparrow_H^G(g) = \frac{1}{|H|} \sum_{\{x : x^{-1}gx \in H\}} \chi(x^{-1}gx).$$

EXAMPLE 27.2

In Assignment 4, we computed the character table of $G = \langle y \mid y^7 = 1 \rangle \rtimes \langle x \mid x^3 = 1 \rangle$ with $xyx^{-1} = y^2$. We can compute the irreducible characters of degree 3 more easily by using induced representations. Let $W = \mathbb{C}$ be a 1-dimensional representation of $H = \langle y \rangle$ with action

$$y^j \cdot 1 = \zeta^j,$$

where $\zeta = e^{2\pi i/7}$ is a 7-th root of unity. Notice that $G = H \cup xH \cup x^2H$, so $\mathbb{C}[G] \otimes_{\mathbb{C}[H]} W$ has basis $\{v_1, v_2, v_3\}$, where $v_1 = 1 \otimes 1$, $v_2 = x \otimes 1$, and $v_3 = x^2 \otimes 1$. Observe that

$$x \cdot v_1 = v_2,$$

$$x \cdot v_2 = v_3,$$

$$x \cdot v_3 = v_1.$$

This gives us

$$\rho(x) = \begin{pmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix},$$

which has trace 0, so $\chi(x) = \chi(x^2) = 0$.

On the other hand, we compute

$$\begin{aligned} y \cdot v_1 &= y \cdot 1 \otimes 1 = 1 \otimes (y \cdot 1) = \zeta \cdot v_1, \\ y \cdot v_2 &= y \cdot x \otimes 1 = x(x^{-1}yx) \otimes 1 = xy^4 \otimes 1 = x \otimes (y^4 \cdot 1) = \zeta^4 \cdot v_2, \\ y \cdot v_3 &= y \cdot x^2 \otimes 1 = x^2(x^{-2}yx^2) \otimes 1 = x^2y^2 \otimes 1 = x^2 \otimes (y^2 \cdot 1) = \zeta^2 \cdot v_3. \end{aligned}$$

Therefore, we obtain

$$\rho(y) = \begin{pmatrix} \zeta & 0 & 0 \\ 0 & \zeta^4 & 0 \\ 0 & 0 & \zeta^2 \end{pmatrix},$$

so $\chi(y) = \zeta + \zeta^2 + \zeta^4$. Then, we can deduce that

$$\chi(y^3) = \chi(y^6) = \chi(y^{-1}) = \overline{\chi(y)} = \zeta^3 + \zeta^5 + \zeta^6.$$

We can extend the above formula to general class functions.

DEFINITION 27.3

Let H be a subgroup of G . Let $f : H \rightarrow k$ be a class function where k is a field. Then we define

$$f \uparrow_H^G (g) := \frac{1}{|H|} \sum_{\{x \in G : x^{-1}gx \in H\}} f(x^{-1}gx).$$

In particular, $\chi \uparrow_H^G$ is the character of the induced representation from H to G with character χ .

PROPOSITION 27.4: TRANSITIVITY OF INDUCTION

Let $H \leq G \leq K$ be groups, and let $f : H \rightarrow k$ be a class function. Then $(f \uparrow_H^G) \uparrow_G^K = f \uparrow_H^K$.

PROOF. We'll prove this using a routine calculation, but we note that this can be done in a coordinate-free way by using tensor products, which we leave to Assignment 5. For $u \in K$, we have

$$\begin{aligned} (f \uparrow_H^G) \uparrow_G^K (u) &= \frac{1}{|G|} \sum_{\{x \in K : x^{-1}ux \in G\}} f \uparrow_H^G (x^{-1}ux) \\ &= \frac{1}{|G|} \sum_{\{x \in K : x^{-1}ux \in G\}} \left(\frac{1}{|H|} \sum_{\{y \in G : y^{-1}(x^{-1}ux)y \in H\}} f(y^{-1}(x^{-1}ux)y) \right) \\ &= \frac{1}{|G|} \frac{1}{|H|} \sum_{\{x \in K : x^{-1}ux \in G\}} \sum_{\{y \in G : y^{-1}x^{-1}uxy \in H\}} f(y^{-1}x^{-1}uxy). \end{aligned}$$

Notice that $y^{-1}x^{-1}uxy \in H$ with $y \in G$ implies that $x^{-1}ux \in yHy^{-1} \in G$. Now, by making the substitution $z = xy$, we obtain

$$\begin{aligned} (f \uparrow_H^G) \uparrow_G^K (u) &= \frac{1}{|G|} \frac{1}{|H|} \sum_{\{z \in K : z^{-1}uz \in H\}} \sum_{y \in G} f(z^{-1}uz) \\ &= \frac{1}{|G|} \frac{1}{|H|} \sum_{\{z \in K : z^{-1}uz \in H\}} |G| f(z^{-1}uz) \\ &= f \uparrow_H^K (u). \end{aligned}$$

□

28 Frobenius reciprocity (11/15/2021)

Let H be a subgroup, and let W be a left $k[H]$ -module. Then $W \uparrow_H^G = k[G] \otimes_{k[H]} W$ is a left $k[G]$ -module. We saw in the previous lecture that

$$\chi_W \uparrow_H^G (g) = \frac{1}{|H|} \sum_{\{x \in G : x^{-1}gx \in H\}} \chi_W(x^{-1}gx).$$

Also, if G has disjoint coset decomposition $x_1H \cup \dots \cup x_mH$, then

$$\chi_W \uparrow_H^G (g) = \sum_{\{i : x_i^{-1}gx_i \in H\}} \chi_W(x_i^{-1}gx_i).$$

REMARK 28.1

If H is a normal subgroup of G , then

$$\chi_W \uparrow_H^G (g) = \begin{cases} 0 & \text{if } g \notin H, \\ \frac{1}{|H|} \sum_{x \in G} \chi_W(x^{-1}gx) & \text{if } g \in H, \end{cases}$$

since $x^{-1}gx \in H$ if and only if $g \in xHx^{-1} = H$.

Let V be a left $k[G]$ -module. We have a left $k[H]$ -module $V \downarrow_H^G$ by taking V as a set, but we only remember the $k[H]$ -module structure. That is, we have $V \downarrow_H^G = k[H]V$. If χ_V is the character of V , then

$$\chi_V \downarrow_H^G (h) = \chi_V(h)$$

for all $h \in H$. Indeed, we have $\chi_V \downarrow_H^G (h) = \text{Tr}(\rho(h))$, where $\rho(h) : V \rightarrow V$ is given by $v \mapsto h \cdot v$. But $h \in H \subseteq G$, so this is just the trace of the particular element $\rho(h)$, which is $\chi_V(h)$.

THEOREM 28.2: FROBENIUS RECIPROCITY

Let $\phi : G \rightarrow \mathbb{C}$ and $\psi : H \rightarrow \mathbb{C}$ be class functions, where $H \leq G$ are finite groups. Then

$$\langle \psi \uparrow_H^G, \phi \rangle_G = \langle \psi, \phi \downarrow_H^G \rangle_H.$$

PROOF. As with the transitivity of induction, this can also be done using a high level proof, but we will do this using a straightforward computation. We have

$$\begin{aligned} \langle \psi \uparrow_H^G, \phi \rangle_G &= \frac{1}{|G|} \sum_{g \in G} \psi \uparrow_H^G (g) \phi(g^{-1}) \\ &= \frac{1}{|G|} \sum_{g \in G} \left(\frac{1}{|H|} \sum_{\{x \in G : x^{-1}gx \in H\}} \psi(x^{-1}gx) \right) \phi(g^{-1}) \\ &= \frac{1}{|G|} \frac{1}{|H|} \sum_{g \in G} \sum_{\{x \in G : x^{-1}gx \in H\}} \psi(x^{-1}gx) \phi(g^{-1}). \end{aligned}$$

Now, substitute $h = x^{-1}gx$ so that $g = xhx^{-1}$ and $g^{-1} = xh^{-1}x^{-1}$. Then, we obtain

$$\begin{aligned}\langle \psi \uparrow_H^G, \phi \rangle_G &= \frac{1}{|G|} \frac{1}{|H|} \sum_{h \in H} \sum_{x \in G} \psi(h) \phi(xh^{-1}x^{-1}) \\ &= \frac{1}{|G|} \frac{1}{|H|} \sum_{h \in H} |G| \psi(h) \phi(h^{-1}) \\ &= \frac{1}{|H|} \sum_{h \in H} \psi(h) \phi(h^{-1}) \\ &= \langle \psi, \phi \downarrow_H^G \rangle_H,\end{aligned}$$

where the second equality is because ϕ is a class function, which yields $\phi(xh^{-1}x^{-1}) = \phi(h^{-1})$. \square

This result has a nice connection with tensor-hom adjunction. Let W be a left $k[H]$ -module and let V be a left $k[G]$ -module. Then we have a k -algebra isomorphism

$$\text{Hom}_{k[G]}(k[G] \otimes_{k[H]} W, V) \cong \text{Hom}_{k[H]}(W, \text{Hom}_{k[G]}(k[G], V)).$$

This essentially states that if we have a tensor on the left, then we can move it over.

How is this the same as Frobenius reciprocity? We have the nice fact that if V_1 and V_2 are left $k[G]$ -modules where k is algebraically closed, then

$$\dim_k \text{Hom}_{k[G]}(V_1, V_2) = \langle \chi_{V_1}, \chi_{V_2} \rangle.$$

Somehow, the category of representations sees the character table. Let's consider the case where V_1 and V_2 are simple. If V_1 and V_2 are non-isomorphic, then both values are 0. On the other hand, if V_1 and V_2 are isomorphic, then Schur's lemma tells us that $\text{Hom}_{k[G]}(V_1, V_2)$ is just k , so these are both equal to 1. Now, suppose that V and W are general left $k[G]$ -modules with decompositions $V \cong V_1^{a_1} \oplus \cdots \oplus V_s^{a_s}$ and $W \cong V_1^{b_1} \oplus \cdots \oplus V_s^{b_s}$ where V_1, \dots, V_s are simple. Then

$$\text{Hom}_{k[G]}(V, W) \cong k^{a_1 b_1 + \cdots + a_s b_s},$$

which is just $\langle \chi_V, \chi_W \rangle$.

Now, let W be a left $k[H]$ -module and V be a left $k[G]$ -module. Then we have

$$\dim_k \text{Hom}_{k[G]}(k[G] \otimes_{k[H]} W, V) = \dim_k \text{Hom}_{k[G]}(W \uparrow_H^G, V) = \langle \chi_W \uparrow_H^G, \chi_V \rangle_G.$$

On the other hand, we can see that

$$\dim_k \text{Hom}_{k[H]}(W, {}_{k[H]}V) = \langle \chi_W, \chi_V \downarrow_H^G \rangle_H.$$

Hence, the above isomorphism gives us Frobenius reciprocity.

Let $\text{fix}_n(\sigma)$ be the number of fixed points of $\sigma \in S_n$. Recall that we had

$$\frac{1}{n!} \sum_{\sigma \in S_n} \text{fix}_n(\sigma) = 1$$

for all $n \geq 1$, and

$$\frac{1}{n!} \sum_{\sigma \in S_n} \text{fix}_n(\sigma)^2 = 2$$

for all $n \geq 2$. First, we'll give an easy proof of the first result. Write $\text{fix}_n = X_1 + \cdots + X_n$ where each X_i is a random variable given by

$$X_i(\sigma) = \begin{cases} 1 & \text{if } \sigma(i) = i, \\ 0 & \text{otherwise.} \end{cases}$$

We can think of the quantity on the left as the expected value of the number of fixed points for a given $\sigma \in S_n$. Then it follows that

$$\mathbb{E}(\text{fix}_n) = \mathbb{E}(X_1) + \cdots + \mathbb{E}(X_n) = \frac{1}{n} + \cdots + \frac{1}{n} = 1.$$

However, we can't extend this proof to the second result. Instead, we can use Frobenius reciprocity!

REMARK 28.3

Let S_n act on $\{1, \dots, n\}$ as usual. Let H be the subgroup of S_n consisting of elements that fix n , and note that $H \cong S_{n-1}$. Then we will show on the assignment that

$$\chi_{\text{triv}} \uparrow_H^{S_n}(\sigma) = \text{fix}_n(\sigma),$$

where χ_{triv} is the trivial character on H .

Let's give another proof of the first fact. Let χ'_{triv} be the trivial character on S_n . By Frobenius reciprocity, we obtain

$$\langle \chi_{\text{triv}} \uparrow_H^{S_n}, \chi'_{\text{triv}} \rangle_{S_n} = \langle \chi_{\text{triv}}, \chi'_{\text{triv}} \downarrow_H^{S_n} \rangle_H = \langle \chi_{\text{triv}}, \chi_{\text{triv}} \rangle_H = 1.$$

On the other hand, we see that

$$\langle \chi_{\text{triv}} \uparrow_H^{S_n}, \chi'_{\text{triv}} \rangle_{S_n} = \langle \text{fix}_n, \chi'_{\text{triv}} \rangle_{S_n} = \frac{1}{n!} \sum_{\sigma \in S_n} \text{fix}(\sigma),$$

and this gives the result. Now, let $n \geq 2$. Applying Frobenius reciprocity, we have

$$\begin{aligned} \langle \chi_{\text{triv}} \uparrow_H^{S_n}, \text{fix}_n \rangle_{S_n} &= \langle \chi_{\text{triv}}, \text{fix}_n \downarrow_H^{S_n} \rangle_H \\ &= \langle \chi_{\text{triv}}, \chi_{\text{triv}} + \text{fix}_{n-1} \rangle_{S_{n-1}} \\ &= \langle \chi_{\text{triv}}, \chi_{\text{triv}} \rangle_{S_{n-1}} + \langle \chi_{\text{triv}}, \text{fix}_{n-1} \rangle_{S_{n-1}} \\ &= 1 + 1 = 2. \end{aligned}$$

The second equality is because n is fixed in H , so this proves the second fact.

In fact, we have the following more general result.

PROPOSITION 28.4

Let $m \leq n$ be positive integers. Then we have

$$\frac{1}{n!} \sum_{\sigma \in S_n} \text{fix}_n(\sigma)^m = B_m,$$

where B_m is the number of partitions of $\{1, \dots, m\}$, called the m -th Bell number.

PROOF. We proceed by induction on m . We have already proved this for $m = 1$ and $m = 2$. Notice that

$$\langle \chi_{\text{triv}} \uparrow_H^{S_n}, \text{fix}_n^{m-1} \rangle_{S_n} = \langle \text{fix}_n, \text{fix}_n^{m-1} \rangle_{S_n} = \frac{1}{n!} \sum_{\sigma \in S_n} \text{fix}(\sigma) \text{fix}(\sigma)^{m-1} = \frac{1}{n!} \sum_{\sigma \in S_n} \text{fix}(\sigma)^m.$$

On the other hand, Frobenius reciprocity gives us

$$\begin{aligned} \langle \chi_{\text{triv}} \uparrow_H^{S_n}, \text{fix}_n^{m-1} \rangle_{S_n} &= \langle \chi_{\text{triv}}, \text{fix}_n^{m-1} \downarrow_H^{S_n} \rangle_H \\ &= \langle \chi_{\text{triv}}, (1 + \text{fix}_{n-1})^{m-1} \rangle_{S_{n-1}} \\ &= \sum_{j=0}^{m-1} \binom{m-1}{j} \langle \chi_{\text{triv}}, \text{fix}_{n-1}^j \rangle_{S_{n-1}}. \end{aligned}$$

We have $j \leq m-1 \leq n-1$, so by the induction hypothesis, we obtain

$$\langle \chi_{\text{triv}}, \text{fix}_{n-1} \rangle_{S_{n-1}} = \frac{1}{(n-1)!} \sum_{\sigma \in S_{n-1}} \text{fix}(\sigma)^j = B_j.$$

In order to prove the result, it suffices to show that

$$\sum_{j=0}^{m-1} \binom{m-1}{j} B_j = \sum_{j=0}^{m-1} \binom{m-1}{m-1-j} B_j = B_m.$$

To see this, note that m has to be in one of the sets. Pick $m-1-j$ other elements to be in the same set as m . Then the remaining j elements form a partition, which yields the desired identity. \square

29 Inducing up and restricting down (11/19/2021)

Let $H \leq G$ be groups, and let χ be a character on H . We'll be working towards Mackey's criterion, which gives us sufficient and necessary conditions for $\chi \uparrow_H^G$ to be irreducible.

Recall that if χ is a character on G , then χ is irreducible if and only if $\langle \chi, \chi \rangle_G = 1$. So to start, we require that $\langle \chi \uparrow_H^G, \chi \uparrow_H^G \rangle_G = 1$ in order for $\chi \uparrow_H^G$ to be irreducible. By Frobenius reciprocity, we obtain

$$\langle \chi, \chi \uparrow_H^G \downarrow_H^G \rangle_H = \langle \chi \uparrow_H^G, \chi \uparrow_H^G \rangle_G = 1.$$

To understand this, we need to know the effect of inducing up and then restricting down. Let $H, K \leq G$ be groups, and let χ be a character on H . What is the character $\chi \uparrow_H^G \downarrow_K^G$ on K ?

First, we'll review double cosets. For $H, K \leq G$, we put an equivalence relation on G by setting $g_1 \sim g_2$ if and only if there exist elements $k \in K$ and $h \in H$ such that $g_1 = kg_2h$. Let's verify that this is indeed an equivalence relation. Observe that we have reflexivity by taking $k = h = 1$. To see that \sim is symmetric, notice that $g_1 = kg_2h$ implies that $g_2 = k^{-1}g_1h^{-1}$. Finally, \sim is transitive since $g_1 = kg_2h$ and $g_2 = k'g_3h'$ implies that $g_1 = kk'g_3h'h$ with $kk' \in K$ and $h'h \in H$. It follows that \sim partitions G into disjoint sets called double cosets, and these are equivalence classes under \sim . For $g \in G$, we write

$$[g]_{\sim} = \{kg_1h : k \in K, h \in H\} = Kg_1H.$$

Write $G = Ks_1H \cup \dots \cup Ks_rH$ where s_1, \dots, s_r is a complete set of double coset representatives. Given a double coset representative $s \in G$, we let $H_s := K \cap sHs^{-1}$. If we have a character χ on H , then we get a new character χ_s on H_s defined by $\chi_s(shs^{-1}) := \chi(h)$. To see that χ_s is a character, note that χ is a character by assumption, so there exists a representation $\rho : H \rightarrow \text{GL}_d(\mathbb{C})$ such that $\chi = \text{Tr}(\rho)$. Define $\tilde{\rho} : sHs^{-1} \rightarrow \text{GL}_d(\mathbb{C})$ by $\tilde{\rho}(shs^{-1}) = \rho(h)$. This is a group homomorphism since

$$\tilde{\rho}(sh_1s^{-1}sh_2s^{-1}) = \tilde{\rho}(sh_1h_2s^{-1}) = \rho(h_1h_2) = \rho(h_1)\rho(h_2) = \tilde{\rho}(sh_1s^{-1})\tilde{\rho}(sh_2s^{-1}).$$

By restricting to H_s , we have the map

$$\tilde{\rho}|_{H_s} : K \cap sHs^{-1} \rightarrow \text{GL}_d(\mathbb{C}),$$

and we can take $\chi_s = \text{Tr}(\tilde{\rho}|_{H_s})$.

THEOREM 29.1

Let $H, K \leq G$ be groups, and let χ be a character on H . Then we have

$$\chi \uparrow_H^G \downarrow_K^G = \sum_{i=1}^r \chi_{s_i} \uparrow_{H_{s_i}}^K,$$

where $G = Ks_1H \cup \dots \cup Ks_rH$ and $H_{s_i} = K \cap s_iHs_i^{-1}$ for $i = 1, \dots, r$.

For $i = 1, \dots, r$, observe that we have

$$H_{s_i} = K \cap s_i H s_i^{-1} \subseteq K.$$

Let $T_i \subseteq K$ be a set of left coset representatives for K/H_{s_i} so that

$$K = \bigcup_{x \in T_i} x H_{s_i}.$$

We claim that $\{x s_i : 1 \leq i \leq r, x \in T_i\}$ is a complete set of left coset representatives of H in G . First, we need to show that the cosets $x s_i H$ are pairwise disjoint. Suppose that $x \in T_i$ and $y \in T_j$ with $x \neq y$ if $i \neq j$. We show that $x s_i H \neq y s_j H$.

Suppose that $x s_i H = y s_j H$. Then $x s_i H \in K s_i H$ since $x \in K$ and $y s_j H \in K s_j H$ since $y \in K$. This gives us $K s_i H \cap K s_j H \neq \emptyset$, so $s_i = s_j$. Now, assume that we have $x s_i H = y s_i H$. Then we get $x s_i H s_i^{-1} = y s_i H s_i^{-1}$. In particular, notice that $y^{-1} x \in s_i H s_i^{-1} \cap K = H_{s_i}$, so $x = y$. Thus, the left cosets $x s_i H$ are all pairwise disjoint.

Next, we show that each $g \in G$ is in one of the cosets $x s_i H$. First, there exists a unique $1 \leq i \leq r$ such that $g \in K s_i H$. Write $g = k s_i h$ for some $k \in K$ and $h \in H$. Then, there exists a unique $x \in T_i$ such that $k \in x H s_i$. This gives $g \in k s_i H = x \theta s_i H$ for some $\theta \in H_{s_i} = K \cap s_i H s_i^{-1}$. It follows that $\theta = s_i h_0 s_i^{-1}$ for some $h_0 \in H$. Finally, we obtain $g \in x \theta s_i H = x (s_i h_0 s_i^{-1}) s_i H = x s_i H$, which proves the claim.

Now that we have established that $\{x s_i : 1 \leq i \leq r, x \in T_i\}$ forms a complete set of left coset representatives of H in G , we can prove Theorem 29.1.

PROOF OF THEOREM 29.1. Let $k \in K$. Notice that $x^{-1} k x \in H_{s_i} = s_i H s_i^{-1} \cap K$, so we can write $x^{-1} k x = s_i h s_i^{-1}$ if $x^{-1} k x \in H_{s_i}$. Then $s_i^{-1} x^{-1} k x s_i = h$, so we get

$$\begin{aligned} \chi_{s_i} \uparrow_{H_{s_i}}^K (k) &= \sum_{\{x \in T_i : x^{-1} k x \in H_{s_i}\}} \chi_{s_i} (x^{-1} k x) \\ &= \sum_{\{x \in T_i : x^{-1} k x \in H_{s_i}\}} \chi_{s_i} (s_i h s_i^{-1}) \\ &= \sum_{\{x \in T_i : x^{-1} k x \in H_{s_i}\}} \chi(h) \\ &= \sum_{\{x \in T_i : x^{-1} k x \in H_{s_i}\}} \chi(s_i^{-1} x^{-1} h x s_i). \end{aligned}$$

Next, we'll look at the left side of the equation. First, we immediately notice that $\chi \uparrow_H^G \downarrow_K^G (k) = \chi \uparrow_H^G (k)$. Since G has left coset decomposition given by $G = \bigcup_{i=1}^r \bigcup_{x \in T_i} x s_i H$, it follows that

$$\begin{aligned} \chi \uparrow_H^G (k) &= \sum_{i=1}^r \sum_{\{x \in T_i : (x s_i)^{-1} k (x s_i) \in H\}} \chi((x s_i)^{-1} k (x s_i)) \\ &= \sum_{i=1}^r \sum_{\{x \in T_i : s_i^{-1} x^{-1} k x s_i \in H\}} \chi(s_i^{-1} x^{-1} k x s_i). \end{aligned}$$

Note that $s_i^{-1} x^{-1} k x s_i \in H$ if and only if $x^{-1} k x \in s_i H s_i^{-1}$. Moreover, we have $T_i \subseteq K$, so $x^{-1} k x \in K$ as well. Hence, we have $x^{-1} k x \in H_{s_i} = K \cap s_i H s_i^{-1}$, so we obtain

$$\chi \uparrow_H^G (k) = \sum_{i=1}^r \sum_{\{x \in T_i : x^{-1} k x \in H_{s_i}\}} \chi(s_i^{-1} x^{-1} k x s_i) = \sum_{i=1}^r \chi \uparrow_{H_{s_i}}^K (k),$$

and this completes the proof. \square

30 Mackey's criterion, unitary operators (11/22/2021)

Let $H \leq G$ be groups, and let χ be a character on H . When is $\chi \uparrow_H^G$ irreducible? Recall that we showed that $\chi \uparrow_H^G$ is irreducible if and only if

$$\langle \chi, \chi \uparrow_H^G \downarrow_H^G \rangle_H = \langle \chi \uparrow_H^G, \chi \uparrow_H^G \rangle_G = 1$$

by applying Frobenius reciprocity. Now, let $G = Hs_1H \cup \cdots \cup Hs_rH$ be the double coset decomposition of G . We may assume that $s_1 = 1$ as it must be in one of the double cosets. In particular, notice that $Hs_1H = H \cdot 1 \cdot H = H$. By Theorem 29.1, we obtain

$$\chi \uparrow_H^G \downarrow_H^G = \sum_{i=1}^r \chi_{s_i} \uparrow_{H_{s_i}}^H,$$

where $H_{s_i} = H \cap s_i H s_i^{-1}$ and $\chi_{s_i}(s_i h s_i^{-1}) = \chi(h)$. Therefore, $\chi \uparrow_H^G$ being irreducible is equivalent to

$$\left\langle \chi, \sum_{i=1}^r \chi_{s_i} \uparrow_{H_{s_i}}^H \right\rangle_H = 1.$$

Since $\chi_{s_1} = \chi \uparrow_H^H = \chi$, we obtain

$$\left\langle \chi, \chi + \sum_{i=2}^r \chi_{s_i} \uparrow_{H_{s_i}}^H \right\rangle_H = \langle \chi, \chi \rangle_H + \sum_{i=2}^r \langle \chi, \chi_{s_i} \uparrow_{H_{s_i}}^H \rangle_H = 1.$$

Note that $\langle \chi, \chi \rangle_H = 1$ and $\langle \chi, \chi_{s_i} \uparrow_{H_{s_i}}^H \rangle_H \geq 0$ for all $i = 2, \dots, r$. Therefore, we see that $\chi \uparrow_H^G$ is irreducible if and only if χ is irreducible and $\langle \chi, \chi_{s_i} \uparrow_{H_{s_i}}^H \rangle_H = 0$ for all $i = 2, \dots, r$. Here, we notice that $s_i \notin H$ for all $i = 2, \dots, r$. This gives us Mackey's criterion.

THEOREM 30.1: MACKEY'S CRITERION

Let $H \leq G$ be groups, and let χ be a character on H . Then the induced character $\chi \uparrow_H^G$ is irreducible if and only if χ is irreducible and $\langle \chi, \chi_{s_i} \uparrow_{H_{s_i}}^H \rangle_H = 0$ for all $s_i \in G \setminus H$.

EXAMPLE 30.2

Let $G = \langle x, y \mid x^3 = y^7 = 1, xyx^{-1} = y^2 \rangle$. Let $H = \langle y \rangle$. Define a character on H by $\chi(y) = e^{2\pi i/7}$, which is irreducible since it is of degree 1. Notice that $H \trianglelefteq G$, so we have $G = H \cup HxH \cup Hx^2H$ since

$$HxH = x(x^{-1}Hx)H = xHH = xH,$$

and similarly, $Hx^2H = x^2H$. Moreover, we also have

$$H_x = H \cap xHx^{-1} = H,$$

$$H_{x^2} = H \cap x^2Hx^{-2} = H.$$

By definition, we have $\chi_x(xyx^{-1}) = \chi(y) = e^{2\pi i/7}$. This yields $\chi_x(y^2) = e^{2\pi i/7}$ and hence

$$\chi_x(y) = \chi_x(y^8) = \chi_x(y^2)^4 = e^{8\pi i/7}.$$

On the other hand, note that $\chi_{x^2}(y^4) = \chi_{x^2}(x^2yx^{-2}) = e^{2\pi i/7}$, which implies that

$$\chi_{x^2}(y) = \chi_{x^2}(y^8) = \chi_{x^2}(y^4)^2 = e^{4\pi i/7}.$$

Finally, notice that $H_x = H_{x^2} = H$, so $\chi_x \uparrow_{H_x}^H = \chi_x$ and $\chi_{x^2} \uparrow_{H_{x^2}}^H = \chi_{x^2}$. These are both distinct characters from χ by our above calculations, so $\langle \chi, \chi_x \rangle_H = \langle \chi, \chi_{x^2} \rangle_H = 0$. Thus, Mackey's criterion holds in this case.

We've now reached the end of the syllabus, but not the end of the lecture period. Let's now focus on some results about subgroups of $\mathrm{GL}_d(\mathbb{C})$, since representation theory at its heart is about looking at images of groups inside $\mathrm{GL}_d(\mathbb{C})$. Some of these are more useful in the context of representations of infinite groups, but Jordan's theorem, which we will soon give, is a very useful for representations of finite groups. In many of these theorems, we will give explicit bounds; these will not be the best bounds, but are done for the sake of proving that explicit bounds exist.

THEOREM 30.3: JORDAN'S THEOREM

Let $d \geq 1$ be an integer. Then there exists an integer $N = N(d)$ such that if G is a finite subgroup of $\mathrm{GL}_d(\mathbb{C})$, then G has an abelian subgroup of index at most $N(d)$.

When G is small, this doesn't say much, as the trivial group has index at most $N(d)$ if $|G| \leq N(d)$. On the other hand, this is very useful when G is large, as it says that G is "almost abelian". As an application, we can use this to prove results about representations of S_n . The proof of Jordan's theorem requires some analysis, so we'll recall some of the results as we go.

Let G be a finite group, and let V be a left $\mathbb{C}[G]$ -module so that $V \cong \mathbb{C}^d$ as a \mathbb{C} -vector space. We can define an inner product between $v = (v_1, \dots, v_d)^T$ and $w = (w_1, \dots, w_d)^T$ by

$$\langle v, w \rangle = \sum_{i=1}^d v_i \overline{w_i}.$$

Recall that an operator $U : V \rightarrow V$ is **unitary** if $\langle Uv, w \rangle = \langle v, U^{-1}w \rangle$ for all $v, w \in V$. For all $g \in G$, we have a linear map $L_g : V \rightarrow V$ defined by $L_g(v) = g \cdot v$, but note that L_g is not unitary in general. To get around this, we can construct a new inner product by

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

where $\langle \cdot, \cdot \rangle$ in the sum is our ordinary Euclidean inner product over \mathbb{C}^d .

EXERCISE 30.4

Verify that $\langle \cdot, \cdot \rangle_G$ defined as above is an inner product.

PROPOSITION 30.5

The operators $L_g : V \rightarrow V$ are unitary with respect to the inner product $\langle \cdot, \cdot \rangle_G$.

PROOF. We need to show that $\langle L_g v, w \rangle_G = \langle v, L_{g^{-1}} w \rangle_G$, since $L_{g^{-1}}$ is the inverse of L_g . First, we have

$$\langle L_g v, w \rangle_G = \frac{1}{|G|} \sum_{x \in G} \langle x L_g v, x w \rangle = \frac{1}{|G|} \sum_{x \in G} \langle x g v, x w \rangle.$$

By substituting $y = xg$, we obtain

$$\langle L_g v, w \rangle_G = \frac{1}{|G|} \sum_{y \in G} \langle y v, y g^{-1} w \rangle = \frac{1}{|G|} \sum_{y \in G} \langle y v, y L_{g^{-1}} w \rangle = \langle v, L_{g^{-1}} w \rangle_G. \quad \square$$

This is very useful for computations. Let V be a representation, and let W be a subrepresentation of V . If we define

$$W^\perp := \{v \in V : \langle v, w \rangle_G = 0 \text{ for all } w \in W\},$$

then $V = W \oplus W^\perp$. Note that W^\perp is another representation, because if we take $u \in W^\perp$, $g \in G$, and $w \in W$, then we obtain

$$\langle g \cdot u, w \rangle_G = \langle u, g^{-1} \cdot w \rangle_G = 0$$

as $g^{-1} \cdot w \in W$. Then $u \in W^\perp$ implies that $g \cdot u \in W^\perp$.

Note that $M_d(\mathbb{C})$ has a norm, called the **operator norm**, which is defined by

$$\|A\| := \sup_{|v|_G=1} \sqrt{\langle Av, Av \rangle_G},$$

where $|v|_G = \sqrt{\langle v, v \rangle_G}$. In particular, this satisfies $\|A + B\| \leq \|A\| + \|B\|$, and this turns $M_d(\mathbb{C})$ into a metric space where the distance from A to B is given by $\|A - B\|$.

Let \mathcal{U} be the set of all unitary matrices in $M_d(\mathbb{C})$. Then \mathcal{U} is compact; that is, every open cover has a finite subcover. Note that $M_d(\mathbb{C})$ is finite-dimensional over \mathbb{C} , so by Heine-Borel, this is equivalent to saying that \mathcal{U} is closed and bounded. To see that \mathcal{U} is bounded, take $A \in \mathcal{U}$. Then we have

$$\langle Av, Av \rangle_G = \langle v, A^{-1}Av \rangle_G = \langle v, v \rangle_G,$$

which implies that $\|A\| = 1$, because if we are given v on the unit ball (any v having inner product 1 with itself), then Av is also on the unit ball. This is called being an isometry; it preserves distance. To see that \mathcal{U} is closed, recall that for any $A \in M_d(\mathbb{C})$, there exists $A^* \in M_d(\mathbb{C})$, called the **adjoint**, such that $\langle Av, w \rangle = \langle v, A^*w \rangle$, with A being unitary if and only if $A^{-1} = A^*$. Define the map $f : M_d(\mathbb{C}) \rightarrow M_d(\mathbb{C})$ by

$$f(A) = AA^*.$$

We leave it as an exercise to show that f is continuous. Now, $\{I\}$ is closed, and the preimage of a closed set under a continuous map is closed, so it follows that $f^{-1}(\{I\}) = \mathcal{U}$ is closed. Therefore, \mathcal{U} is compact.

31 Some lemmas for Jordan's theorem (11/24/2021)

Recall that we are trying to prove Jordan's theorem, which states that if $d \geq 1$ is an integer, then there exists an integer $N = N(d)$ such that if G is a finite subgroup of $\text{GL}_d(\mathbb{C})$, then G has an abelian subgroup of index at most $N(d)$. Notice that $G \leq \mathcal{U}$, where \mathcal{U} is the group of unitary matrices. We saw last time that \mathcal{U} is compact.

Let $U \in \mathcal{U}$ be unitary. Then for any v with $|v| = 1$, we have

$$|Uv| = \langle Uv, Uv \rangle^{1/2} = \langle v, U^{-1}Uv \rangle^{1/2} = \langle v, v \rangle^{1/2} = |v|.$$

Therefore, if $A \in M_d(\mathbb{C})$, then $\|UA\| = \|AU\| = \|A\|$. Indeed, notice that

$$\|UA\| = \sup_{|v|=1} |UA v| = \sup_{|v|=1} |Av| = \|A\|,$$

and the argument for $\|AU\| = \|A\|$ is analogous.

Since $\mathcal{U} \subseteq M_d(\mathbb{C})$ is compact, we know that for any $\varepsilon > 0$, there exists $R = R(d, \varepsilon)$ such that \mathcal{U} can be covered by R open balls of radius ε (this is a finite subcover).

LEMMA 31.1

Let $G \leq \mathcal{U}$ and let $H \leq G$ be the subgroup generated by $G \cap B(I, 2\varepsilon)$. Then $[G : H] \leq R(d, \varepsilon)$.

PROOF. Suppose that $[G : H] = r > R(d, \varepsilon)$. Then we can write $G = A_1H \cup \cdots \cup A_rH$ as a disjoint union of cosets. Since \mathcal{U} is covered by $R(d, \varepsilon)$ open balls and $r > R(d, \varepsilon)$, there exist integers $i \neq j$ such that $A_i, A_j \in B(X, \varepsilon)$ for some $X \in M_d(\mathbb{C})$ by the pigeonhole principle. In particular, note that

$$\|A_i - A_j\| = \|A_i - X + X - A_j\| \leq \|A_i - X\| + \|X - A_j\| < 2\varepsilon.$$

Note that $A_i^{-1} \in \mathcal{U}$, so we have

$$\|A_i^{-1}(A_i - A_j)\| = \|I - A_i^{-1}A_j\| < 2\varepsilon.$$

This implies that $A_i^{-1}A_j \in G \cap B(I, 2\varepsilon) \subseteq H$, and hence $A_j \in A_iH$, which is a contradiction. \square

It can be shown that we can choose $R(d, \varepsilon) \leq (4/\varepsilon)^{d^2}$.

Next, we make an observation. If $A, B \in \mathcal{U} \cap B(I, \varepsilon)$, then $BA \in \mathcal{U}$ as well, so we obtain

$$\begin{aligned} \|ABA^{-1}B^{-1} - I\| &= \|(ABA^{-1}B^{-1} - I)BA\| \\ &= \|AB - BA\| \\ &= \|(A - I)(B - I) - (B - I)(A - I)\| \\ &\leq \|A - I\|\|B - I\| + \|B - I\|\|A - I\| \\ &< 2\varepsilon^2. \end{aligned}$$

By choosing $\varepsilon < 1/2$, we see that the commutator of A and B is closer to I than A and B . For our purposes, we will pick $\varepsilon = \frac{1}{10d}$, which is certainly less than $1/2$.

LEMMA 31.2

Let $A \in \mathrm{SL}_d(\mathbb{C}) \cap \mathcal{U}$. Suppose that $A = \lambda I$ for some $\lambda \in \mathbb{C}$ and $A \in B(I, \varepsilon)$. Then we have $A = I$.

PROOF. Since $A \in \mathcal{U}$ and $A = \lambda I$ for $\lambda \in \mathbb{C}$, we have

$$\|A - I\| = \|\lambda I - I\| = |\lambda - 1|\|I\| = |\lambda - 1| < \varepsilon.$$

Moreover, we have $\det A = 1$ since $A \in \mathrm{SL}_d(\mathbb{C})$, so $\lambda^d = 1$. Then $\lambda = e^{2\pi i j/d}$ for some $j = \{0, \dots, d-1\}$. Thus, we obtain

$$|\lambda - 1| = |e^{2\pi i j/d} - 1| = \left| \cos\left(\frac{2\pi j}{d}\right) + i \sin\left(\frac{2\pi j}{d}\right) - 1 \right| < \varepsilon.$$

This means that $|\sin(2\pi j/d)| < \varepsilon$. By some elementary calculus, we obtain the inequalities $2x/\pi \leq \sin x \leq x$ for $x \in [0, \pi/2]$. Now, if $|\sin(2\pi j/d)| \neq 0$, then

$$\left| \sin\left(\frac{2\pi j}{d}\right) \right| \geq \sin\left(\frac{\pi}{d}\right) \geq \frac{2}{\pi} \cdot \frac{\pi}{d} = \frac{2}{d} > \frac{1}{10d} = \varepsilon.$$

Thus, it must be the case that $\sin(2\pi j/d) = 0$, as we had $|\sin(2\pi j/d)| < \varepsilon$. It follows that $\lambda = \cos(2\pi j/d) \in \{1, -1\}$. But $|\lambda - 1| = 2 > \varepsilon$, so we must have $\lambda = 1$, and $A = I$ as required. \square

LEMMA 31.3

Let $G \leq \mathcal{U}$ be finite, and let H be the subgroup of G generated by $G \cap B(I, \varepsilon)$. Then either every element of H is a scalar multiple of I , or there exists $z \in H$ which is central in H and is not a scalar multiple of I .

PROOF. Let $\mathcal{B} = \{B_1, \dots, B_m\} = G \cap B(I, \varepsilon)$. If B_1, \dots, B_m are all scalar multiples of I , then we're already done. So without loss of generality, pick $B \in \{B_1, \dots, B_m\}$ such that B is not a scalar multiple of I , and $\|B - I\| \leq \|B_j - I\|$ whenever B_j is not a scalar multiple of I .

We claim that B is central in H . It suffices to show that $BB_j B^{-1} B_j^{-1} = I$ for all $B_j \in \mathcal{B}$. First, since $\varepsilon < 1/2$, we obtain

$$\|BB_j B^{-1} B_j^{-1} - I\| < 2\varepsilon^2 < \varepsilon.$$

In fact, we have

$$\|BB_j B^{-1} B_j^{-1} - I\| \leq 2\|B - I\|\|B_j - I\| < 2\varepsilon\|B - I\| < \|B - I\|.$$

Since B is minimal with respect to the distance from I for non-scalar multiples of I in \mathcal{B} , we see that $BB_j B^{-1} B_j^{-1} = B_k$ for some $k \in \{1, \dots, m\}$, and B_k is a scalar multiple of I . Observe that $\det B_k = 1$ so that $B_k \in \text{SL}_d(\mathbb{C})$. By Lemma 31.2, it follows that $B_k = I$. Thus, $BB_j = B_j B$ for all $B_j \in \mathcal{B}$, so we conclude that B is central in H . \square

Now, we can start by giving a sketch of the proof of Jordan's theorem. We know that $G \leq \mathcal{U}$, and we can cover \mathcal{U} with $R = R(d, \varepsilon)$ balls of radius $\frac{1}{2}\varepsilon = \frac{1}{20d}$.

Let H be the subgroup of G generated by $G \cap B(I, \varepsilon)$. We showed in Lemma 31.1 that $[G : H] \leq R$. By Lemma 31.3, either everything in H is of the form λI for some $\lambda \in \mathbb{C}$, in which case we're already done, or there exists $z \in H$ such that z is not a scalar multiple of I and z is central in H .

Notice that $\text{GL}_d(\mathbb{C})$ acts on $\mathbb{C}^d = V$. Pick an eigenvalue α of z . Let $W = \ker(z - \alpha I)$. Now, we have $(0) \subsetneq W \subsetneq V$. Indeed, by definition of α being an eigenvalue, $z - \alpha I$ must have some kernel. On the other hand, we have $W \subsetneq V$ since z is not a scalar multiple of I .

Now, W is invariant under H , because for $w \in W$ and $h \in H$, we have

$$(z - \alpha I)(h \cdot w) = (hz - \alpha hI) \cdot w = h(z - \alpha I) \cdot w = 0,$$

which implies that $h \cdot w \in W$.

By Maschke, we have $V = W \oplus W'$ where W and W' are both H -invariant. This means that if we take a new basis for $V = W \oplus W'$ where $\{w_1, \dots, w_e\}$ is a basis for W and $\{w_{e+1}, \dots, w_d\}$ is a basis for W' , then the elements of H with respect to this new basis are of the form

$$\begin{pmatrix} \rho_1(h) & 0 \\ 0 & \rho_2(h) \end{pmatrix},$$

where $\rho_1(h)$ is an $e \times e$ matrix, and $\rho_2(h)$ is a $(d - e) \times (d - e)$ matrix. The idea here is that we can proceed by induction. We've broken it up into smaller blocks, and we can apply the induction hypothesis to these smaller blocks. If we get a big abelian subgroup in each block, then we can put these together to get a big abelian subgroup for H !

32 Proof of Jordan's theorem (11/26/2021)

We prove another lemma towards Jordan's theorem.

LEMMA 32.1

Let H_1, \dots, H_k be groups, and suppose that each H_i has an abelian subgroup A_i of index at most n_i . If $H \leq H_1 \times \dots \times H_k$, then H has an abelian subgroup of index at most $n_1 \dots n_k$.

PROOF. Let $A = A_1 \times \dots \times A_k \subseteq H_1 \times \dots \times H_k$. Note that A is abelian as each A_i is abelian. Notice that

$$[H_1 \times \dots \times H_k : A] = [H_1 : A_1] \dots [H_k : A_k] = n_1 \dots n_k.$$

Now, let $B = A \cap H$, which is still abelian. It remains to show that $[H : B] \leq [H_1 \times \cdots \times H_k : A] = n_1 \cdots n_k$. Let X be the set of left cosets of B in H , and let Y be the set of left cosets of A in $H_1 \times \cdots \times H_k$. Define $f : X \rightarrow Y$ by

$$f(hB) = hA.$$

To see that f is well-defined, suppose that $h_1B = h_2B$. This tells us that $h_2^{-1}h_1 \in B \subseteq A$, so $h_1 \in h_2A$, and hence $h_1A = h_2A$. Now, we show that f is injective. Suppose that $f(h_1B) = f(h_2B)$. Then $h_1A = h_2A$, and hence $h_2^{-1}h_1 \in A \cap H = B$. It follows that $h_1B = h_2B$, so f is indeed injective. Thus, we have $[H : B] = |X| \leq |Y| = [H_1 \times \cdots \times H_k : A]$. \square

PROOF OF JORDAN'S THEOREM. We proceed by induction on d . For $d = 1$, we have $\text{GL}_1(\mathbb{C}) = \mathbb{C}^*$, which is abelian, so we can take $N(1) = 1$. Now, suppose that the result holds up to $d - 1$. Define

$$N(d) = R\left(d, \frac{1}{20d}\right) \cdot \left[\max_{1 \leq e \leq d-1} N(e)N(d-e) \right],$$

where $R(d, \varepsilon)$ is the number of open ε -balls needed to cover $\mathcal{U} \subseteq \text{GL}_d(\mathbb{C})$.

We claim that G has an abelian subgroup of index at most $N(d)$. We showed in Lemma 31.1 that if $H \leq G$ is generated by $G \cap B(I, \frac{1}{10d})$, then $[G : H] \leq R(d, \frac{1}{20d})$. So it suffices to show that H has an abelian subgroup B of index at most $\max_{1 \leq e \leq d-1} N(e)N(d-e)$. Indeed, notice that

$$[G : B] = [G : H][H : B] \leq R\left(d, \frac{1}{20d}\right) \cdot [H : B].$$

We have also showed that there exists $e \in \{1, \dots, d-1\}$ such that

$$h \in H \mapsto \begin{pmatrix} \rho_1(h) & 0 \\ 0 & \rho_2(h) \end{pmatrix}$$

where $\rho_1(h)$ is an $e \times e$ matrix and $\rho_2(h)$ is a $(d-e) \times (d-e)$ matrix. Let $H_1 = \{\rho_1(h) : h \in H\} \leq \text{GL}_e(\mathbb{C})$ and $H_2 = \{\rho_2(h) : h \in H\} \leq \text{GL}_{d-e}(\mathbb{C})$. By induction, there exists an abelian subgroup $A_1 \leq H_1$ of index at most $N(e)$, and an abelian subgroup $A_2 \leq H_2$ of index at most $N(d-e)$. Consider the map

$$\begin{aligned} H &\rightarrow H_1 \times H_2, \\ h &\mapsto (\rho_1(h), \rho_2(h)). \end{aligned}$$

By Lemma 32.1, there exists an abelian subgroup $B \leq H$ such that

$$[H : B] \leq N(e)N(d-e) \leq \max_{1 \leq e \leq d-1} N(e)N(d-e),$$

which completes the proof. \square

PROPOSITION 32.2

If $H \leq G$ are groups and $[G : H] = n$, then there exists $H_0 \leq H$ such that $H_0 \trianglelefteq G$ and $[G : H_0] \leq n!$.

PROOF. Let X be the set of left cosets $\{x_1H, \dots, x_mH\}$. Without loss of generality, suppose that $x_1 = 1$. Let G act on X by $g \cdot (x_iH) = gx_iH = x_jH$ for some j . An action of G on X induces a homomorphism

$$\phi : G \rightarrow \text{Sym}_X = \{f : X \rightarrow X \mid f \text{ is bijective}\}$$

given by $\phi(g) = \sigma$ where $g \cdot x_iH = x_{\sigma(i)}H$. Let $H_0 = \ker \phi \trianglelefteq G$. Notice that G/H_0 embeds into Sym_X . In particular, if $|X| < \infty$, then $[G : H_0] \leq |X|!$. In our case, we have $|X| = n$, so $[G : H_0] \leq n!$. Finally, notice that $H_0 \leq H$ since

$$\begin{aligned} \ker \phi &= \{g \in G : gx_iH = x_iH \text{ for all } i = 1, \dots, m\} \\ &= \{g \in G : gx_1H = x_1H\} \\ &= \{g \in G : gH = H\} = H. \end{aligned} \quad \square$$

We give a nice application of this result.

EXAMPLE 32.3

Let $n \geq 5$. If $H \leq S_n$ and $[S_n : H] < n$, then $H = A_n$ or $H = S_n$.

PROOF. Suppose that $[S_n : H] = r < n$. Then by Proposition 32.2, there exists $H_0 \trianglelefteq S_n$ such that $[S_n : H_0] \leq r!$. Notice that $[S_n : A_n] \leq 2$, which implies that $[A_n : A_n \cap H_0] \leq r!$ with $A_n \cap H_0 \trianglelefteq A_n$. Now, A_n is simple for $n \geq 5$, so either $H_0 = A_n$ or $H_0 = \{1\}$. If $H_0 = \{1\}$, then

$$[A_n : H_0] = |A_n| = \frac{n!}{2} \leq r! \leq (n-1)!.$$

Now $n! \leq 2(n-1)!$, so $n \leq 2$, which is a contradiction. So we must have $H_0 = A_n$, in which case $H \geq H_0$, so $H = A_n$ or $H = S_n$. \square

Proposition 32.2 also implies the following extension of Jordan's theorem; we leave the proof as an exercise.

THEOREM 32.4

If $G \leq \text{GL}_d(\mathbb{C})$ is finite, there exists $M = M(d)$ such that G has a normal abelian subgroup of index $M(d)$. In fact, we can take $M(d) = N(d)!$.

Now, we'll start looking at another theorem by Burnside. In 1902, Burnside wondered that if every element of a group G is finite, then is G finite? It is clear that this is false in general by taking

$$G = \bigoplus_{i=1}^{\infty} \mathbb{Z}/2\mathbb{Z}.$$

But what if G is finitely generated? It turns out this is still false. In 1964, Golod and Schafarevich showed that there exist finitely generated groups that are infinite, but every element has finite order. However, we have the special case that if $G \leq \text{GL}_d(\mathbb{C})$ is finitely generated with every element having finite order, then G is in fact finite. This is called the Burnside-Schur theorem, which we will work towards proving.

PROPOSITION 32.5

Let $R \subseteq M_n(\mathbb{C})$ be a \mathbb{C} -submodule of $M_n(\mathbb{C})$. Then either $R = M_n(\mathbb{C})$, or after a change of basis, elements of R can be put in block triangular form

$$\begin{pmatrix} * & * \\ 0 & * \end{pmatrix},$$

where the $*$ on the upper left is $e \times e$ and the $*$ on the bottom right is $(n - e) \times (n - e)$ for some $e \in \{1, \dots, n-1\}$.

PROOF. Let $V = \mathbb{C}^{n \times 1}$, which is a left R -module and right $M_n(\mathbb{C})$ -module. Also, V is faithful since it is faithful as an $M_n(\mathbb{C})$ -module. If V is simple, then the Jacobson density theorem tells us that $R = \text{End}_R(V) = M_n(\mathbb{C})$. On the other hand, if V is not simple, then there exists an R -submodule $0 \subsetneq W \subsetneq V$ of dimension e . Let v_1, \dots, v_e be a basis for W . We can extend this to a basis v_1, \dots, v_n for V , in which case we can write

$$r \mapsto \begin{pmatrix} * & * \\ 0 & * \end{pmatrix}$$

with respect to this new basis. \square

33 Another theorem by Burnside (11/29/2021)

Let $R \subseteq M_d(\mathbb{C})$ be a \mathbb{C} -submodule. Recall that either $R = M_d(\mathbb{C})$, or after a change of basis, every element of R can be put into block triangular form.

LEMMA 33.1

Let $N \geq 2$. Let $G \leq \mathrm{GL}_d(\mathbb{C})$ be a group in which every element has order at most N . Then $|G| \leq N^{2d^3}$.

PROOF. Let $A \in G \leq \mathrm{GL}_d(\mathbb{C})$. Since every element in G has order at most N , the eigenvalues of A belong to the set

$$\Omega = \{\omega \in \mathbb{C}^* : \omega^j = 1 \text{ for some } 1 \leq j \leq N\}.$$

Notice that $|\Omega| = 1 + 2 + \cdots + N \leq N^2$. Next, notice that if $A \in G$, then $\mathrm{Tr}(A) \in \mathbb{X}$, where

$$\mathbb{X} := \{\omega_1 + \cdots + \omega_d : \omega_1, \dots, \omega_d \in \Omega\}.$$

We see that $|\mathbb{X}| \leq |\Omega|^d \leq N^{2d}$.

Now, we'll proceed by induction on d . For $d = 1$, we have $G \leq \mathbb{C}^*$, and in fact, $G \leq \Omega$, so $|G| \leq N^2$. Assume that the result holds up to $d - 1$. Let R be the \mathbb{C} -span of all the elements in G ; note that $R \subseteq M_d(\mathbb{C})$. We can see that R is a \mathbb{C} -algebra since

$$\left(\sum \lambda_A A\right) \left(\sum \gamma_B B\right) = \sum \lambda_A \gamma_B AB.$$

Using Proposition 32.5, we can break this into two cases.

CASE 1. Suppose that $R = M_d(\mathbb{C})$. Then there exist $Y_1, \dots, Y_d \in G$ which form a basis for $M_d(\mathbb{C})$.

CLAIM. If $A, B \in M_d(\mathbb{C})$ and $\mathrm{Tr}(AY_i) = \mathrm{Tr}(BY_i)$ for all $i = 1, \dots, d$, then $A = B$.

PROOF OF CLAIM. Letting $C = A - B$ and using the fact that trace is linear, it suffices to show that $\mathrm{Tr}(CY_i) = 0$ for all $i = 1, \dots, d$ implies that $C = 0$. So let $C = (c_{ij}) \in M_d(\mathbb{C})$, and let $C^* = (\bar{c}_{ij})$. Then we have $\mathrm{Tr}(CC^*) = \sum |c_{ij}|^2$. If we write $C^* = \sum_{i=1}^d \lambda_i Y_i$, we get

$$\mathrm{Tr}(CC^*) = \mathrm{Tr}\left(C \left(\sum_{i=1}^d \lambda_i Y_i\right)\right) = \sum_{i=1}^d \lambda_i \mathrm{Tr}(CY_i) = 0,$$

where the last equality is by assumption, so $C = 0$. ■

Now, consider the map $\Psi : G \rightarrow \mathbb{X}^{d^2}$ given by

$$\Psi(A) = (\mathrm{Tr}(AY_1), \dots, \mathrm{Tr}(AY_d)).$$

By the claim, this map is injective, so we obtain $|G| \leq |\mathbb{X}|^{d^2} \leq |\mathbb{X}|^{d^3}$.

CASE 2. Suppose that $R \subsetneq M_d(\mathbb{C})$. Then after a change of basis, we can assume that

$$G \subseteq R \subseteq \left\{ \begin{pmatrix} *_1 & * \\ 0 & *_2 \end{pmatrix} : *_1 \in M_e(\mathbb{C}), *_2 \in M_{d-e}(\mathbb{C}) \right\}$$

for some $1 \leq e \leq d - 1$. So we can write each $A \in G$ in the form

$$A = \begin{pmatrix} A_{11} & A_{12} \\ 0 & A_{22} \end{pmatrix}$$

where $A_{11} \in \text{GL}_e(\mathbb{C})$ and $A_{22} \in \text{GL}_{d-e}(\mathbb{C})$. Since A has order at most N , there exists $j \in \{1, \dots, n\}$ such that $A^j = I$. Then we obtain

$$A^j = \begin{pmatrix} A_{11}^j & * \\ 0 & A_{22}^j \end{pmatrix} = \begin{pmatrix} I_e & 0 \\ 0 & I_{d-e} \end{pmatrix} = I.$$

Hence, we have $A_{11}^j = I_e$ and $A_{22}^j = I_{d-e}$. Define the groups

$$\begin{aligned} G_1 &= \{A_{11} : A \in G\} \leq \text{GL}_e(\mathbb{C}), \\ G_2 &= \{A_{22} : A \in G\} \leq \text{GL}_{d-e}(\mathbb{C}). \end{aligned}$$

Every element of G_1 has order at most N , and every element of G_2 also has order at most N . By the induction hypothesis, we have $|G_1| \leq N^{2e^3}$ and $|G_2| \leq N^{2(d-e)^3}$. It follows that

$$|G_1||G_2| \leq N^{2(e^3+(d-e)^3)} \leq N^{2d^3}.$$

To finish the proof, it remains to show that $|G| \leq |G_1||G_2|$. Suppose otherwise that $|G| > |G_1||G_2|$. Then by the pigeonhole principle, we can find $B_1 \in G_1$ and $B_2 \in G_2$ such that there are distinct elements $A, A' \in G$ of the form

$$A = \begin{pmatrix} B_1 & C \\ 0 & B_2 \end{pmatrix}, \quad A' = \begin{pmatrix} B_1 & C' \\ 0 & B_2 \end{pmatrix},$$

where $C \neq C'$. We see that

$$I \neq A(A')^{-1} = \begin{pmatrix} B_1 B_1^{-1} & * \\ 0 & B_2 B_2^{-1} \end{pmatrix} = \begin{pmatrix} I_e & D \\ 0 & I_{d-e} \end{pmatrix}$$

where $D \neq 0$. But $A(A')^{-1} \in G$, so there exists $j \in \{1, \dots, n\}$ such that $[A(A')^{-1}]^j = I$. This implies that

$$\begin{pmatrix} I_e & D \\ 0 & I_{d-e} \end{pmatrix}^j = I,$$

so we must have $D = 0$, which is a contradiction. \square

We note that this result is false if we are working over a field of characteristic p , where p is a prime. Indeed, take the group

$$G = \left\{ \begin{pmatrix} 1 & a \\ 0 & 1 \end{pmatrix} : a \in \mathbb{F}_p(t) \right\} \leq \text{GL}_2(\mathbb{F}_p(t)).$$

Then for any $a \in \mathbb{F}_p(t)$, we have

$$\begin{pmatrix} 1 & a \\ 0 & 1 \end{pmatrix}^p = \left[\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}^p + \begin{pmatrix} 0 & a \\ 0 & 0 \end{pmatrix}^p \right] = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}^p + \begin{pmatrix} 0 & a \\ 0 & 0 \end{pmatrix}^p = I.$$

Burnside used the above lemma to prove the following result.

THEOREM 33.2: BURNSIDE

Let $G \leq \text{GL}_d(\mathbb{Q})$ be a group in which element has finite order. Then G is finite.

Recall that for $n \in \mathbb{N}$, the Euler totient function is given by $\phi(n) = \#\{1 \leq m \leq n : \gcd(m, n) = 1\}$. Moreover, we have $\lim_{n \rightarrow \infty} \phi(n) = \infty$, and it satisfies

$$\phi(p_1^{a_1} \cdots p_s^{a_s}) = p_1^{a_1} \cdots p_s^{a_s} \left(1 - \frac{1}{p_1}\right) \cdots \left(1 - \frac{1}{p_s}\right).$$

Note that for all $n \in \mathbb{N}$, we have $\phi(n) \geq \sqrt{n}/2$. To see this, let $p \geq 3$ be prime and $a \geq 1$ be an integer. Then

$$\phi(p^a) = p^a \left(1 - \frac{1}{p}\right) \geq p^{a/2}.$$

Now, writing $n = 2^{b_1} p_2^{b_2} \cdots p_s^{b_s}$ where p_2, \dots, p_s are distinct odd primes, we have

$$\phi(n) = \begin{cases} 2^{b_1-1} \phi(p_2^{b_2}) \cdots \phi(p_s^{b_s}) & \text{if } b_1 \geq 1, \\ \phi(p_2^{b_2}) \cdots \phi(p_s^{b_s}) & \text{if } b_1 = 0. \end{cases}$$

In particular, we see that

$$\phi(n) \geq \frac{2^{b_1/2}}{2} p_2^{b_2/2} \cdots p_s^{b_s/2} = \frac{\sqrt{n}}{2}.$$

LEMMA 33.3

Let $d \geq 1$. Then there exists an integer $n = n(d)$ such that if $A \in \text{GL}_d(\mathbb{C})$ has finite order, then the order of A is at most n .

PROOF. Let $P(x) = x^d + c_{d-1}x^{d-1} + \cdots + c_0 \in \mathbb{Q}[x]$ be the characteristic polynomial of A . If ω is an eigenvalue of A , then $P(\omega) = 0$. This means that

$$[\mathbb{Q}(\omega) : \mathbb{Q}] \leq d$$

since $P(x)$ has degree at most d . Now, if $\omega = e^{2\pi i j/b}$ where $\gcd(j, b) = 1$ (that is, ω is a b -th root of unity), then it can be shown that

$$[\mathbb{Q}(\omega) : \mathbb{Q}] = \phi(b).$$

Note that $\phi(b) \leq d$. Since $\phi(n) \rightarrow \infty$ as $n \rightarrow \infty$, there exists $n = n(d)$ such that $\phi(j) > d$ for all $j \geq n$. So every eigenvalue of A is a b -th root of unity where $b \leq n = n(d)$. Recall that

$$A \sim \begin{pmatrix} \omega_1 & & 0 \\ & \ddots & \\ 0 & & \omega_n \end{pmatrix},$$

so $A^{n!} = I$. Thus, A has order at most $n!$. □

Notice that taking $N = \max(n(d), 2)$ and applying Lemma 33.1 shows that $G \leq \text{GL}_d(\mathbb{Q})$ is finite when every element of G has finite order.

34 Burnside-Schur (12/01/2021)

Now, we'll turn to proving the strengthening of Burnside's result due to Schur. First, we need to say a few words on transcendence bases.

Let K/F be a field extension. A subset $S \subseteq K$ is said to be **algebraically independent** over F if whenever $\{a_1, \dots, a_\ell\} \subseteq S$ is a finite subset and $P(t_1, \dots, t_\ell) \in F[t_1, \dots, t_\ell]$, then $P(a_1, \dots, a_\ell) = 0$ implies that $P \equiv 0$.

For example, $\{\pi\} \subseteq \mathbb{C}$ is algebraically independent over \mathbb{Q} , whereas $\{\sqrt{2}, e\}$ is not since we can take $P(t_1, t_2) = t_1^2 - 2$. An open problem: is $\{e, \pi\}$ algebraically independent over \mathbb{Q} ?

A **transcendence basis** for K/F is then a maximal algebraically independent subset $S \subseteq K$ over F , and these exist by Zorn's lemma.

EXERCISE 34.1

All transcendence bases for K/F have the same cardinality.

We say that a field extension K/F is **finitely generated** if there exists $s \in \mathbb{N}$ and $a_1, \dots, a_s \in \mathbb{K}$ such that $K = F(a_1, \dots, a_s)$.

Notice that $\mathbb{Q}(\sqrt{2}, \sqrt{3})/\mathbb{Q}$ and $\mathbb{Q}(\pi, e, \sqrt{2})/\mathbb{Q}$ are finitely generated extensions, but \mathbb{C}/\mathbb{Q} is not finitely generated since $\mathbb{Q}(a_1, \dots, a_s)$ is countable for any $a_1, \dots, a_s \in \mathbb{C}$.

If K/F is a finitely generated extension, there exists $r \in \mathbb{N}$ and $t_1, \dots, t_r \in K$ which are algebraically independent over F such that $[K : F(t_1, \dots, t_r)] < \infty$. To see why, write $K = F(a_1, \dots, a_m)$. Pick $S \subseteq \{a_1, \dots, a_m\}$ to be a maximal algebraically independent subset. After relabelling, we may assume that $S = \{a_1, \dots, a_r\}$. Let $E = F(a_1, \dots, a_r) \cong F(t_1, \dots, t_r)$. Notice that by construction, each a_i is algebraic over E for $i = r+1, \dots, m$. Since $K = E(a_{r+1}, \dots, a_m)$, we have

$$[K : E] = [E(a_{r+1}, \dots, a_m) : E(a_{r+1}, \dots, a_{m-1})] \cdots [E(a_{r+1}) : E(a_r)] \leq \prod_{i>r} [E(a_i) : E] < \infty.$$

Let's now state the Burnside-Schur theorem.

THEOREM 34.2: BURNSIDE-SCHUR

Let $G \leq \text{GL}_n(\mathbb{C})$ be a finitely generated torsion subgroup. Then G is finite.

Now, let's suppose $G \leq \text{GL}_n(\mathbb{C})$ is generated by $\{A_1^{\pm 1}, \dots, A_r^{\pm 1}\}$, where

$$A_i = \begin{pmatrix} a_{11}^{(i)} & \cdots & a_{1n}^{(i)} \\ \vdots & \ddots & \vdots \\ a_{n1}^{(i)} & \cdots & a_{nn}^{(i)} \end{pmatrix}, \quad A_i^{-1} = \begin{pmatrix} b_{11}^{(i)} & \cdots & b_{1n}^{(i)} \\ \vdots & \ddots & \vdots \\ b_{n1}^{(i)} & \cdots & b_{nn}^{(i)} \end{pmatrix}.$$

Let $K = \mathbb{Q}(\{a_{ij}^{(s)}, b_{ij}^{(s)} : 1 \leq i, j \leq n, 1 \leq s \leq r\})$, which is a finitely generated extension of \mathbb{Q} with $K \subseteq \mathbb{C}$. In fact, we have $G \leq \text{GL}_n(K)$ since $\text{GL}_n(K)$ is a group containing all generators of G .

Suppose $A \in \text{GL}_n(K)$ has finite order. We have seen that

$$A \sim \begin{pmatrix} \omega_1 & & 0 \\ & \ddots & \\ 0 & & \omega_n \end{pmatrix}$$

where $\omega_1, \dots, \omega_n$ are the eigenvalues of A , and they are n -th roots of unity.

We have showed that there are only finitely many roots of unity ω with $[\mathbb{Q}(\omega) : \mathbb{Q}] \leq n$. Schur proved that this extends to finitely generated extensions of \mathbb{Q} .

THEOREM 34.3: SCHUR

Let K be a finitely generated extension of \mathbb{Q} . For each $n \geq 1$, there are only finitely many roots of unity ω with $[K(\omega) : K] \leq n$.

By applying the same argument as Burnside, the Burnside-Schur theorem follows.

Now, let's prove Schur's result. Suppose that K has transcendence degree $M < \infty$. It suffices to prove the result for a purely transcendental extension $K = \mathbb{Q}(t_1, \dots, t_s)$. To see why, notice that if we have a general finitely generated extension K/\mathbb{Q} , then

$$[K(\omega) : K] \leq [K(\omega) : \mathbb{Q}(t_1, \dots, t_s)] = [K(\omega) : K][K : \mathbb{Q}(t_1, \dots, t_s)] \leq n \cdot M.$$

LEMMA 34.4

Let t_1, \dots, t_s be algebraically independent over \mathbb{Q} . Then

$$[\mathbb{Q}(t_1, \dots, t_s)(\omega)] = \mathbb{Q}(t_1, \dots, t_s) = [\mathbb{Q}(\omega) : \mathbb{Q}].$$

PROOF. Notice that $[\mathbb{Q}(t_1, \dots, t_s)(\omega)] = \mathbb{Q}(t_1, \dots, t_s)$ is the degree of the minimal polynomial of ω with coefficients in $\mathbb{Q}(t_1, \dots, t_s)$, which is at most the degree of the minimal polynomial of ω with coefficients in \mathbb{Q} .

For the reverse inequality, suppose m is the degree of the minimal polynomial of ω with coefficients in \mathbb{Q} . Then we can write

$$P_m(t_1, \dots, t_s)\omega^m + \dots + P_0(t_1, \dots, t_s) = 0$$

for some $P_0, \dots, P_m \in \mathbb{Q}[t_1, \dots, t_s]$. We can rewrite this in the form

$$\sum_{i_1, \dots, i_s \geq 0} q_{i_1 \dots i_s}(\omega) t_1^{i_1} \dots t_s^{i_s} = 0$$

where $\deg q_{i_1 \dots i_s} \leq m$. Notice that $q_{i_1 \dots i_s}(\omega) = 0$ for all $i_1, \dots, i_s \geq 0$ since

$$\sum_{i_1, \dots, i_s \geq 0} \left(\sum_{\sigma \in \text{Gal}(\mathbb{Q}(\omega)/\mathbb{Q})} \sigma(\omega^{p_{i_1 \dots i_s}}(\omega)) \right) t_1^{i_1} \dots t_s^{i_s} = 0.$$

Since t_1, \dots, t_s is algebraically independent over \mathbb{Q} , the above coefficients must be 0. Hence, we have $\deg q_{i_1 \dots i_s} \leq [\mathbb{Q}(\omega) : \mathbb{Q}]$, so $m \leq [\mathbb{Q}(\omega) : \mathbb{Q}]$. \square

35 Wedderburn and Lie-Kolchin

We have already seen the Vandermonde determinant in linear algebra, but we'll give an interesting proof of it using abstract algebra.

LEMMA 35.1

We have

$$\det \begin{pmatrix} 1 & 1 & \dots & 1 \\ x_1 & x_2 & \dots & x_n \\ x_1^2 & x_2^2 & \dots & x_n^2 \\ \vdots & \vdots & \ddots & \vdots \\ x_1^{n-1} & x_2^{n-1} & \dots & x_n^{n-1} \end{pmatrix} = \prod_{i>j} (x_i - x_j).$$

PROOF. Let $R = \mathbb{Z}[x_1, \dots, x_n]$, and let

$$P = \det \begin{pmatrix} 1 & 1 & \dots & 1 \\ x_1 & x_2 & \dots & x_n \\ x_1^2 & x_2^2 & \dots & x_n^2 \\ \vdots & \vdots & \ddots & \vdots \\ x_1^{n-1} & x_2^{n-1} & \dots & x_n^{n-1} \end{pmatrix} \in R.$$

Notice that for all $i > j$, we have $(x_i - x_j) \mid P$. Indeed, this is because

$$\det \begin{pmatrix} 1 & 1 & \cdots & 1 \\ x_1 & x_2 & \cdots & x_n \\ x_1^2 & x_2^2 & \cdots & x_n^2 \\ \vdots & \vdots & \ddots & \vdots \\ x_1^{n-1} & x_2^{n-1} & \cdots & x_n^{n-1} \end{pmatrix} = \det \begin{pmatrix} 0 & 1 & \cdots & 1 \\ x_1 - x_2 & x_2 & \cdots & x_n \\ x_1^2 - x_2^2 & x_2^2 & \cdots & x_n^2 \\ \vdots & \vdots & \ddots & \vdots \\ x_1^{n-1} - x_2^{n-1} & x_2^{n-1} & \cdots & x_n^{n-1} \end{pmatrix}.$$

Notice that R is a UFD since \mathbb{Z} is a UFD. The $(x_i - x_j)$ are irreducible and pairwise coprime. So we have $\prod_{i>j} (x_i - x_j) \mid P$. Notice that P and $\prod_{i>j} (x_i - x_j)$ both have degree $\binom{n}{2}$, so we see that

$$P = c \prod_{i>j} (x_i - x_j)$$

for some $c \in \mathbb{Z}$. The coefficient of $x_1^0 x_2^1 \cdots x_n^{n-1}$ in P is 1, and it is also 1 in $\prod_{i>j} (x_i - x_j)$. Hence, we must have $c = 1$. \square

THEOREM 35.2

Let k be a field of characteristic 0. Then $A \in M_n(k)$ is nilpotent if and only if $\text{Tr}(A^i) = 0$ for all $i \geq 1$.

PROOF. The forward direction is clear. For the converse, let $\lambda_1, \dots, \lambda_s$ be the distinct nonzero eigenvalues of A . Then A is similar to an upper triangular matrix with the λ_i 's on the diagonal. In particular, we have

$$\text{Tr}(A^i) = c_1 \lambda_1^i + \cdots + c_s \lambda_s^i$$

for some $c_1, \dots, c_s \geq 0$. Since $\text{Tr}(A^i) = 0$ for all $i \geq 1$, we obtain

$$\begin{pmatrix} \lambda_1 & \lambda_2 & \cdots & \lambda_s \\ \lambda_1^2 & \lambda_2^2 & \cdots & \lambda_s^2 \\ \vdots & \vdots & \ddots & \vdots \\ \lambda_1^s & \lambda_2^s & \cdots & \lambda_s^s \end{pmatrix} \begin{pmatrix} c_1 \\ c_2 \\ \vdots \\ c_s \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{pmatrix}.$$

In particular, we see that

$$\det \begin{pmatrix} \lambda_1 & \lambda_2 & \cdots & \lambda_s \\ \lambda_1^2 & \lambda_2^2 & \cdots & \lambda_s^2 \\ \vdots & \vdots & \ddots & \vdots \\ \lambda_1^s & \lambda_2^s & \cdots & \lambda_s^s \end{pmatrix} = \lambda_1 \cdots \lambda_s \det \begin{pmatrix} 1 & 1 & \cdots & 1 \\ \lambda_1 & \lambda_2 & \cdots & \lambda_s \\ \vdots & \vdots & \ddots & \vdots \\ \lambda_1^{s-1} & \lambda_2^{s-1} & \cdots & \lambda_s^{s-1} \end{pmatrix} = \lambda_1 \cdots \lambda_s \prod_{i>j} (\lambda_i - \lambda_j) \neq 0,$$

since the λ_i 's are distinct and nonzero. It follows that $c_i = 0$ for all $i = 1, \dots, s$, so A is nilpotent. \square

DEFINITION 35.3

A nonempty set \mathcal{S} is a **semigroup** if it has a binary operation \cdot that is associative. We say that \mathcal{S} is a **monoid** if there exists an element $1 \in \mathcal{S}$ such that $1 \cdot s = s \cdot 1 = s$ for all $s \in \mathcal{S}$.

If \mathcal{S} is a k -algebra and S is a multiplicatively closed subset of \mathcal{S} , we can always make a k -subalgebra by taking

$$k[\{1\} \cup S] = \left\{ \sum_{s \in S} \lambda_s s + \gamma \cdot 1 : \lambda_s, \gamma \in k, \lambda_s = 0 \text{ for all but finitely many } s \in S \right\}.$$

THEOREM 35.4: WEDDERBURN

Let $S \subseteq M_n(\mathbb{C})$ be a multiplicatively closed set of matrices in which every element is nilpotent. Then there exists a matrix $X \in \text{GL}_n(\mathbb{C})$ such that XSX^{-1} is a subset of upper triangular matrices.

PROOF. Let R be the \mathbb{C} -span of elements from $S \cup \{1\} \subseteq M_n(\mathbb{C})$. Then R is a \mathbb{C} -subalgebra of $M_n(\mathbb{C})$. Assume Wedderburn's result is not true. Pick the smallest $n \geq 1$ for which it fails. Notice that $n \geq 2$ since the only nilpotent 1×1 matrix is the zero matrix, which is always upper triangular.

Recall that either $R = M_n(\mathbb{C})$ or after a change of basis, R is a subset of upper triangular matrices.

CASE 1. Suppose that R is a subset of upper triangular matrices. Then every element $s \in S$ is of the form

$$s = \begin{pmatrix} s_1 & * \\ 0 & s_2 \end{pmatrix}.$$

Take $S_1 = \{s_1 : s \in S\} \subseteq M_d(\mathbb{C})$ and $S_2 = \{s_2 : s \in S\} \subseteq M_{n-d}(\mathbb{C})$. Note that S_1 and S_2 are closed under multiplication since S is also closed under multiplication.

By the minimality of n , there exists $X_1 \in \text{GL}_d(\mathbb{C})$ and $X_2 \in \text{GL}_{n-d}(\mathbb{C})$ such that $X_1 S_1 X_1^{-1}$ and $X_2 S_2 X_2^{-1}$ are both subsets of upper triangular matrices. Then we see that XSX^{-1} is a subset of upper triangular matrices, which is a contradiction.

CASE 2. Suppose that $R = M_n(\mathbb{C})$. Recall that R is the \mathbb{C} -span of $S \cup \{1\}$, so there exists $s_2, \dots, s_n \in S$ such that $\{I, s_2, \dots, s_n\}$ is a basis for $M_n(\mathbb{C})$. Moreover, we showed that if $C \in M_n(\mathbb{C})$, Y_1, \dots, Y_t is a basis for $M_n(\mathbb{C})$, and $\text{Tr}(CY_i) = 0$ for all $i = 1, \dots, t$, then $C = 0$. So let $s \in S$. Notice that $\text{Tr}(sI) = \text{Tr}(s) = 0$ since s is nilpotent, and $\text{Tr}(ss_i) = 0$ for all $i = 2, \dots, n$ since S is multiplicatively closed. Thus, we must have $s = 0$, and so $S \subseteq \{0\}$. Then R is at most 1-dimensional, contradicting the fact that $n \geq 2$. \square

Now, we'll prove the Lie-Kolchin theorem. Recall that a matrix $U \in \text{GL}_n(\mathbb{C})$ is **unipotent** if $U = I + N$ for some nilpotent matrix N . Equivalently, all the eigenvalues of U are 1, and U is similar to a matrix with all ones along the diagonal. A subgroup $G \leq \text{GL}_n(\mathbb{C})$ is **unipotent** if every element $U \in G$ is unipotent.

EXAMPLE 35.5

The discrete Heisenberg group given by

$$\left\{ \begin{pmatrix} 1 & a & b \\ 0 & 1 & c \\ 0 & 0 & 1 \end{pmatrix} : a, b, c \in \mathbb{Z} \right\}$$

is a unipotent group.

THEOREM 35.6: LIE-KOLCHIN

Let $G \leq \text{GL}_n(\mathbb{C})$ be a unipotent group. Then there exists $X \in \text{GL}_n(\mathbb{C})$ such that XGX^{-1} is a subgroup of all upper triangular matrices with ones along the diagonal.

PROOF. Let S be the semigroup generated by all elements of the form $U - I$ with $U \in G$. That is, we have

$$S = \{(U_1 - I) \cdots (U_s - I) : s \geq 1, U_1, \dots, U_s \in G\}.$$

Note that S is multiplicatively closed by definition. We claim that every element of S has trace 0. To see

this, let $(U_1 - I) \cdots (U_s - I) \in S$ for some $s \geq 1$. Notice that

$$(U_1 - I) \cdots (U_s - I) = \sum_{r=0}^d \sum_{1 \leq i_1 < \cdots < i_r \leq d} U_{i_1} \cdots U_{i_r} (-1)^{d-r}.$$

Fix $r \in \{0, \dots, d\}$. Note that $U_{i_1} \cdots U_{i_r}$ is unipotent, so it has trace n . Hence, we obtain

$$\begin{aligned} \text{Tr}((U_1 - I) \cdots (U_s - I)) &= \text{Tr} \left(\sum_{r=0}^d \sum_{1 \leq i_1 < \cdots < i_r \leq d} U_{i_1} \cdots U_{i_r} (-1)^{d-r} \right) \\ &= \sum_{r=0}^d \sum_{1 \leq i_1 < \cdots < i_r \leq d} \text{Tr}(U_{i_1} \cdots U_{i_r}) (-1)^{d-r} \\ &= n \sum_{r=0}^d \sum_{1 \leq i_1 < \cdots < i_r \leq d} (-1)^{d-r} \\ &= n \sum_{r=0}^d \left(\sum_{1 \leq i_1 < \cdots < i_r \leq d} 1 \right) (-1)^{d-r} \\ &= n \sum_{r=0}^d \binom{d}{r} (-1)^{d-r} = n(1-1)^d = 0. \end{aligned}$$

Thus, every element of S has trace 0.

Now, each $A \in S$ is nilpotent. Indeed, since S is multiplicatively closed, we have $A \cdot A = A^2 \in S$, and it follows by induction that $A^i \in S$ for all $i \geq 1$. These all have trace 0, so by Theorem 35.2, A must be nilpotent. By Wedderburn's theorem on semigroups of nilpotent matrices, there exists $X \in \text{GL}_n(\mathbb{C})$ such that XSX^{-1} is a subset of upper triangular matrices. Such upper triangular matrices must have zeros along the diagonal since all the elements of S have trace 0. Finally, if $U \in G$, then we can write $U = I + (U - I)$, with $U - I \in S$. We see that

$$XUX^{-1} = X(I + (U - I))X^{-1} = I + \begin{pmatrix} 0 & & * \\ & \ddots & \\ 0 & & 0 \end{pmatrix} = \begin{pmatrix} 1 & & * \\ & \ddots & \\ 0 & & 1 \end{pmatrix}. \quad \square$$

EXERCISE 35.7

Using this result, show that unipotent groups are solvable.