

Abstract Algebra - Homework 1

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Problem 1

Let $k = \mathbb{F}_7 = \mathbb{Z}/7\mathbb{Z}$. We define $\text{GL}_2(k)$ as the group of all invertible 2×2 matrices with entries in the field k . In other words,

$$\text{GL}_2(k) = \left\{ \begin{pmatrix} a & b \\ c & d \end{pmatrix} \in M_2(k) \mid ad - bc \neq 0 \right\}.$$

$\text{GL}_2(k)$ Forms a Group

Let $A, B \in \text{GL}_2(k)$. Then the product AB is defined as:

$$AB = \begin{pmatrix} ae + bg & af + bh \\ ce + dg & cf + dh \end{pmatrix},$$

where all entries involve only addition and multiplication of elements in k . Since k is a field, it is closed under addition and multiplication, so all entries of AB lie in k . Furthermore, $\det(AB) = \det(A)\det(B) \neq 0$, so $AB \in \text{GL}_2(k)$. Thus, $\text{GL}_2(k)$ is closed under matrix multiplication.

Since matrix multiplication is associative, the operation on $\text{GL}_2(k)$ is associative.

The identity element in $\text{GL}_2(k)$ is the identity matrix

$$I = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}.$$

For any $A \in \text{GL}_2(k)$, we have $AI = IA = A$, and since the entries 1 and 0 are in k , we conclude $I \in \text{GL}_2(k)$.

Since every element of $\text{GL}_2(k)$ is invertible by definition, the inverse of

$$A = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \in \text{GL}_2(k)$$

is given by:

$$A^{-1} = \frac{1}{\det(A)} \begin{pmatrix} d & -b \\ -c & a \end{pmatrix}.$$

Since $a, b, c, d \in k$, and $\det(A) = ad - bc \neq 0$, we have $\frac{1}{\det(A)} \in k$, because k is a field. As k is closed under addition, subtraction, and multiplication, all entries of A^{-1} lie in k . Hence, $A^{-1} \in \text{GL}_2(k)$.

Therefore, $\text{GL}_2(k)$ satisfies the group axioms under matrix multiplication and is a group.

The Center of $\text{GL}_2(k)$

Let $A = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \in \text{GL}_2(k)$. Suppose $A \in Z(\text{GL}_2(k))$. Then for all $B = \begin{pmatrix} e & f \\ g & h \end{pmatrix} \in \text{GL}_2(k)$, we must have

$$AB = BA.$$

Compute both sides:

$$AB = \begin{pmatrix} ae + bg & af + bh \\ ce + dg & cf + dh \end{pmatrix}, \quad BA = \begin{pmatrix} ea + fc & eb + fd \\ ga + hc & gb + hd \end{pmatrix}.$$

For these to be equal for all $e, f, g, h \in k$, compare the corresponding entries:

$$\begin{aligned} ae + bg &= ea + fc & \Rightarrow & b = c = 0 \\ af + bh &= eb + fd & \Rightarrow & a = d, \text{ using } b = 0 \\ ce + dg &= ga + hc & \Rightarrow & c = b = 0 \\ cf + dh &= gb + hd & \Rightarrow & d = a \end{aligned}$$

Hence, A must be of the form:

$$A = \begin{pmatrix} \lambda & 0 \\ 0 & \lambda \end{pmatrix} = \lambda I,$$

where $\lambda \in k^\times = k \setminus \{0\}$ (since A must be invertible). Thus,

$$Z(\text{GL}_2(\mathbb{F}_7)) = \{\lambda I \mid \lambda \in k^\times\}.$$

This center consists of 6 elements and forms an abelian subgroup of $\text{GL}_2(\mathbb{F}_7)$.

Group Action on $\mathbb{P}^1(k)$

We define the projective line over k as $\mathbb{P}^1(k) = k \cup \{\infty\}$. Let $A = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \in \text{GL}_2(k)$. Then the action of $\text{GL}_2(k)$ on $\mathbb{P}^1(k)$ is given by the formula:

$$A \cdot z = \begin{cases} \frac{az + b}{cz + d}, & \text{if } z \in k \text{ and } cz + d \neq 0, \\ \infty, & \text{if } z \in k \text{ and } cz + d = 0, \\ \frac{a}{c}, & \text{if } z = \infty \text{ and } c \neq 0, \\ \infty, & \text{if } z = \infty \text{ and } c = 0. \end{cases}$$

We verify that this defines a group action.

Let $I = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$. Then for all $z \in \mathbb{P}^1(k)$,

$$I \cdot z = \frac{1 \cdot z + 0}{0 \cdot z + 1} = \frac{z}{1} = z, \quad \text{and} \quad I \cdot \infty = \frac{1}{0} := \infty.$$

So the identity acts as the identity function.

Let $A = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$ and $B = \begin{pmatrix} e & f \\ g & h \end{pmatrix}$ be in $\text{GL}_2(k)$, and let $z \in \mathbb{P}^1(k)$.

Then:

$$B \cdot z = \frac{ez + f}{gz + h}, \quad \text{and} \quad A \cdot (B \cdot z) = \frac{a \cdot \left(\frac{ez+f}{gz+h} \right) + b}{c \cdot \left(\frac{ez+f}{gz+h} \right) + d}.$$

Simplifying this gives:

$$A \cdot (B \cdot z) = \frac{(aez + af + bgz + bh)}{(cez + cf + dgz + dh)} = \frac{(ae + bg)z + (af + bh)}{(ce + dg)z + (cf + dh)},$$

which is the action of the product matrix AB on z :

$$(AB) \cdot z.$$

Thus, the compatibility condition holds.

Therefore, the formula defines a group action of $\text{GL}_2(k)$ on $\mathbb{P}^1(k)$.

Transitivity and the Stabilizer of 0

Let $z \in \mathbb{P}^1(k)$ be arbitrary. We want to find a matrix $A \in \text{GL}_2(k)$ such that $A \cdot 0 = z$. Let

$$A = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \in \text{GL}_2(k).$$

Then the action on 0 is given by

$$A \cdot 0 = \frac{b}{d},$$

provided $d \neq 0$. For any $z \in k$, we can take $b = z$ and $d = 1$, with $a \in k^\times$, $c \in k$ arbitrary, such that $\det(A) = ad - bc \neq 0$.

To obtain ∞ , we require $d = 0$, in which case the formula becomes

$$A \cdot 0 = \frac{b}{d} = \infty,$$

provided $b \neq 0$. We can choose $a, c \in k$ arbitrarily so that $\det(A) = -bc \neq 0$, ensuring $A \in \text{GL}_2(k)$.

Hence, for any $z \in \mathbb{P}^1(k)$, there exists a matrix $A \in \text{GL}_2(k)$ such that $A \cdot 0 = z$. Therefore, the action is transitive.

We require $A \cdot 0 = 0$, so $\frac{b}{d} = 0 \Rightarrow b = 0$. Therefore, the stabilizer of 0 is the set of all invertible lower triangular matrices:

$$B = \left\{ \begin{pmatrix} a & 0 \\ c & d \end{pmatrix} \in \text{GL}_2(k) \mid a, d \in k^\times, c \in k \right\}.$$

Kernel of the Action

The kernel of the action can be defined as follows,

$$\ker = \{ A \in \text{GL}_2(k) \mid A \cdot z = z \text{ for all } z \in \mathbb{P}^1(k) \}.$$

Then, for all $z \in k$,

$$\begin{aligned} A \cdot z &= \frac{az + b}{cz + d} = z \\ \implies az + b &= z(cz + d) = cz^2 + dz \\ \implies cz^2 + (d - a)z - b &= 0 \\ \implies c &= 0, \quad d = a, \quad b = 0. \end{aligned}$$

Therefore,

$$A = \begin{pmatrix} a & 0 \\ 0 & a \end{pmatrix} = aI, \quad \text{with } a \in k^\times.$$

These are exactly the scalar matrices which form the center. Hence, the kernel of the action is the center of $\mathrm{GL}_2(k)$.

Intersection of Conjugates of the Stabilizer

Let $B \subseteq \mathrm{GL}_2(k)$ be the stabilizer of $0 \in \mathbb{P}^1(k)$. We claim that

$$\bigcap_{g \in \mathrm{GL}_2(k)} gBg^{-1} = Z(\mathrm{GL}_2(k)).$$

This follows from the general fact that, if a group G acts transitively on a set X , then the intersection of all conjugates of the stabilizer G_x is equal to the kernel of the associated homomorphism:

$$\bigcap_{g \in G} gG_xg^{-1} = \ker(G \rightarrow \mathrm{Sym}(X)).$$

In our case, $G = \mathrm{GL}_2(k)$, $X = \mathbb{P}^1(k)$. We have already shown that the action is transitive, and that the kernel of the action is the center:

$$\ker = Z(\mathrm{GL}_2(k)).$$

Therefore,

$$\bigcap_{g \in \mathrm{GL}_2(k)} gBg^{-1} = Z(\mathrm{GL}_2(k)).$$

Problem 2

Let X be the set of all k -element subsets of $\{1, \dots, n\}$, and let S_n act on X by

$$\sigma \cdot E := \{\sigma(e) \mid e \in E\}.$$

Fix the subset $A = \{1, \dots, k\} \in X$. The stabilizer of A consists of all permutations in S_n that fix A setwise. These are exactly the permutations that act as an element of S_k on the set $\{1, \dots, k\}$, and as an element of S_{n-k} on its complement $\{k+1, \dots, n\}$, independently. Thus,

$$\mathrm{Stab}_{S_n}(A) \cong S_k \times S_{n-k}.$$

By the Orbit-Stabilizer Theorem, the number of k -element subsets is

$$|X| = [S_n : \text{Stab}_{S_n}(A)] = \frac{n!}{k!(n-k)!} = \binom{n}{k}.$$

Problem 3

Group action

Let G be a finite group and $H \subset G$ a subgroup. Define a map

$$\phi : H \times (G/H) \rightarrow G/H, \quad (h, gH) \mapsto (hg)H.$$

To verify that ϕ defines a group action, we check the two axioms. For all $gH \in G/H$,

$$e \cdot gH = (eg)H = gH.$$

For all $h_1, h_2 \in H$ and $gH \in G/H$,

$$h_1 \cdot (h_2 \cdot gH) = h_1 \cdot (h_2gH) = (h_1h_2g)H = ((h_1h_2) \cdot gH).$$

Hence, the identity and compatibility axioms are satisfied. Since we are viewing G/H purely as a set of left cosets (not as a quotient group), this confirms that ϕ defines a group action of H on the set G/H .

Trivial action implies normality

Suppose ϕ is trivial. That means for all $h \in H$ and $gH \in G/H$, we have:

$$\phi(h, gH) = gH \quad \Rightarrow \quad (hg)H = gH.$$

This implies:

$$hg \in gH \quad \Rightarrow \quad g^{-1}hg \in H \quad \text{for all } h \in H, g \in G.$$

Therefore, H is closed under conjugation by elements of G , i.e., $gHg^{-1} \subseteq H$. Since $g \in G$ was arbitrary, it follows that H is a normal subgroup of G .

The action is not transitive

Assume $[G : H] = p$, where p is the smallest prime dividing $|G|$.

Suppose that the action is transitive. Then the orbit of any element $gH \in G/H$ under the action of H is the entire set G/H , which has p elements.

But the size of any orbit under a group action divides the order of the acting group and in this case, $|H| = |G|/p$.

Therefore, the size of the orbit must divide $|H| = |G|/p$, but it is equal to p . Since p is the smallest prime dividing $|G|$, it does not divide $|G|/p$, and thus does not divide $|H|$.

This is a contradiction. Hence, the action cannot be transitive.

Class equation and normality

From the theory of group actions, we have the orbit decomposition:

$$|G/H| = \sum_{i=1}^r |\mathcal{O}_i|,$$

where \mathcal{O}_i are the distinct orbits of the action of H on the set G/H .

Since $|G/H| = p$, a prime number, the possible orbit decompositions are very limited. One possibility is that there is a single orbit of size p , but this would imply that the action is transitive, which we ruled out in the previous section. Another possibility is that there is one orbit of size 1 and one of size $p - 1$, but the size of each orbit must divide $|H| = |G|/p$. Since p is the smallest prime dividing $|G|$, it does not divide $|G|/p$, and therefore cannot divide any orbit size greater than 1.

The only remaining possibility is that all orbits have size 1. That means:

$$(hg)H = gH \quad \forall h \in H, gH \in G/H,$$

which implies $hg \in gH \Rightarrow g^{-1}hg \in H$, i.e., H is invariant under conjugation by all $g \in G$. Therefore, $H \trianglelefteq G$.

Problem 4

Normal subgroup

Let $V_4 = \{\text{Id}, (12)(34), (13)(24), (14)(23)\} \subset S_4$. By definition, V_4 contains the identity element.

To show that V_4 is normal in S_4 , we verify that it is invariant under conjugation. For any $\sigma \in S_4$ and $v \in V_4$, we have $\sigma v \sigma^{-1}$ is again a product of two disjoint transpositions. Since there are exactly three such elements in S_4 , and they form a conjugacy class, it follows that conjugation by any $\sigma \in S_4$ sends elements of V_4 to other elements in V_4 .

Hence, V_4 is closed under conjugation, and we conclude that $V_4 \trianglelefteq S_4$.

An Isomorphism

Consider the subgroup $H = \langle (12), (123) \rangle \subset S_4$. This subgroup permutes the elements $\{1, 2, 3\}$ and fixes 4, so it is isomorphic to S_3 . We identify S_3 with this subgroup H .

We define the map

$$f : S_3 \rightarrow S_4/V_4, \quad f(\sigma) = \sigma V_4.$$

First, it is well-defined: each $\sigma \in S_3$ is interpreted as an element of $H \subset S_4$, and the left coset σV_4 is a valid element of the quotient S_4/V_4 . The map is injective because $H \cap V_4 = \{\text{Id}\}$, so no two distinct elements of H lie in the same coset. It is surjective since H has 6 elements and $|S_4/V_4| = 6$, meaning the image of f exhausts all cosets. Finally, f is a homomorphism: for all $\sigma_1, \sigma_2 \in S_3$, we have

$$f(\sigma_1 \sigma_2) = \sigma_1 \sigma_2 V_4 = \sigma_1 V_4 \cdot \sigma_2 V_4 = f(\sigma_1) f(\sigma_2).$$

Thus, f is a bijective homomorphism and therefore an isomorphism.

Find normal subgroups

We are asked to find the normal subgroups of S_4 that contain V_4 . From group theory, the normal subgroups of S_4 are:

$$\{\text{Id}\}, \quad V_4, \quad A_4, \quad S_4.$$

Here A_4 denotes the alternating group on four letters, the set of all even permutations, so it is normal in S_4 . Moreover, because each element of V_4 is a product of two transpositions (an even permutation), we have $V_4 \subset A_4$. The subgroups that contain V_4 are V_4, A_4, S_4 . These are all normal in S_4 , and there are no other normal subgroups strictly between V_4 and S_4 . Hence, the normal subgroups of S_4 containing V_4 are V_4, A_4, S_4 .