Homework 4
MATH 541: Abstract Algebra 1
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Sec. 3.1: 2, 14, 22, 24, 36, 40, 41

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Let $\varphi : G \to H$ be a homomorphism of groups with kernel K and let $a, b \in \varphi(G)$. Let $X \in G/K$ be the fiber above a and let Y be the fiber above b, i.e., $X = \varphi^{-1}(a), Y = \varphi^{-1}(b)$. Fix an element u of X (so $\varphi(u) = a$). Prove that if $XY = Z$ in the quotient group G/K and w is any member of Z, then there is some $v \in Y$ such that $uv = w$. [Show $u^{-1}w \in Y$]

Proof.

$$Z = XY = \phi^{-1}(a)\phi^{-1}(b) = \phi^{-1}(ab)$$

We know that ϕ is a group homomorphism, so $\phi(xy) = \phi(x)\phi(y)$.
Therefore, $\phi(u^{-1}w) = \phi(u^{-1})\phi(w) = a^{-1}ab = b$, which implies that $u^{-1}w \in Y$. □

14: Consider the additive quotient group $\mathbb{Q}/\mathbb{Z}$

a Show that every coset of $\mathbb{Z}$ in $\mathbb{Q}$ contains exactly one representative $q \in \mathbb{Q}$ in the range $0 \leqslant q < 1$.

b Show that every element of $\mathbb{Q}/\mathbb{Z}$ has finite order but that there are elements of arbitrarily large order.

c Show that $\mathbb{Q}/\mathbb{Z}$ is the torsion subgroup of $\mathbb{R}/\mathbb{Z}$ (cf. Exercise 6, Section 2.1).

d Show that $\mathbb{Q}/\mathbb{Z}$ is isomorphic to the multiplicative group of root of unity in $\mathbb{C}^\times$.

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Proof. a

$$\forall q' \in \mathbb{Q} : q'\mathbb{Z} = \{q' + z : z \in \mathbb{Z}\}, \exists z' \in \mathbb{Z} : q' + z' \in [0, 1), q = q' + z' \implies q\mathbb{Z} = (q' + z')\mathbb{Z}$$

It is easy to see that $(q' + z')\mathbb{Z} = (q')\mathbb{Z}$, which means $q\mathbb{Z} = q'\mathbb{Z}$

b Note $\mathbb{Q}/\mathbb{Z}$ is an equivalence classes based on all $q \in [0, 1)$.

$$\forall q \in \mathbb{Q}/\mathbb{Z}, \exists z_1, z_2 \in \mathbb{Z} : q = \frac{z_1}{z_2}$$

Therefore, the order is $(\text{lcm}(z_1, z_2))/z_1$, which can be arbitrarily large but finite.

c It suffices to show $\mathbb{Q}/\mathbb{Z}$ is a subgroup $\mathbb{R}/\mathbb{Z}$ with question b. We know that the sum of two rational number is a rational number. We also know that the inverse of a rational number is $-q$ which is equivalent to $1 - q$. 0 is clearly a rational number.

d We can just write out the isomorphism.

For all order $z \in \mathbb{Z}$, the root of unity contains exactly z elements such that z is the order of the element.

Therefore, we can just map all element from $\frac{\mathbb{Q}}{\mathbb{Z}}$ to the root of unity with the denominator as the order, and numerator as the index of the element, which is bijective, and vice versa.

□

22:

a Prove that if H and K are normal subgroups of a group G then their intersection $H \cap K$ is also a normal subgroup of G.

b Prove that the intersection of an arbitrary non-empty collection of normal subgroups of a group is a normal subgroup (do not assume the collection is countable).

Proof. *a* Denote $H \cap K = L$

$$\forall l_1, l_2 \in L : l_1 l_2 \in H, l_1 l_2 \in K \implies l_1 l_2 \in L$$

$$\forall l \in L : l^{-1} \in H, l^{-1} \in K \implies l^{-1} \in L$$

$$\forall l \in L : glg^{-1} \in H, glg^{-1} \in K \implies glg^{-1} \in L$$

b There are no difference between the two argument, but just suggesting the element is in all normal subgroups instead of H, K.

□

24: Prove that if $N \trianglelefteq G$ and H is any subgroup of G then $N \cap H \trianglelefteq H$.

Proof. By definition: $\forall g \in G : gN = Ng \implies \forall h \in H : hN = Nh$. Because H is always normal under H. Then, follow last question, we can conclude that $N \cap H \trianglelefteq H$. □

36: Prove that if $G/Z(G)$ is cyclic then G is Abelian. [If $G/Z(G)$ is cyclic with generator $xZ(G)$, show that every element of G can be written in the form $x^a z$ for some integer $a \in \mathbb{Z}$ and some element $z \in Z(G)$.]

Proof. By definition, $Z(G) = \{z \in G | zg = gz\}$.

If $G/Z(G)$ is cyclic, we can write it with one generator $xZ(G)$, which means we can write every element as $x^a Z(G)^a = x^a Z(G)$. By definition of quotient group equivalent class,

$$\forall g \in G : \exists a \in \mathbb{Z}, z \in Z(G) : g = x^a z$$

$$\forall g_1, g_2 \in G : g_1 g_2 = x^{a_1} z_1 x^{a_2} z_2 = z_1 x^{a_1} x^{a_2} z_2 = z_1 x^{a_1+a_2} z_2 = z_1 z_2 x^{a_1+a_2} = z_2 z_1 x^{a_2} x^{a_1} = z_2 x^{a_2} z_1 x^{a_1} = g_2 g_1$$

□

40: Let G be a group, let N be a normal subgroup of G and let $\overline{G} = G/N$. Prove that $\overline{x}$ and $\overline{y}$ commute in $\overline{G}$ if and only if $x^{-1}y^{-1}xy \in N$. (The element $x^{-1}y^{-1}xy$ is called the commutator of x and y and is denoted by $[x, y]$.)

Proof. $\Longleftarrow$

$$x^{-1}y^{-1}xy \in N \implies x \sim xx^{-1}y^{-1}xy = y^{-1}xy \implies yx \sim yy^{-1}xy = xy$$

$\Longrightarrow$
If $\overline{xy} = \overline{yx}$

$$\forall x, y \in \overline{xy} : \overline{xy} = \overline{yx} \implies \overline{x^{-1}y^{-1}xy} = \mathbb{1} \implies x^{-1}y^{-1}xy \in N$$

□

41: Let G be a group. Prove that $N = \langle x^{-1}y^{-1}xy | x, y \in G\rangle$ is a normal subgroup of G and G/N is abelian (N is called the commutator subgroup of G)

Proof. Closed under multiplication and inversion is trivial.
Normal:
Given Lemma, $g^{-1}\langle S\rangle g = \langle g^{-1}Sg\rangle$, it suffices to prove the S is normal.

$$\forall g \in G : \forall x, y \in G : g(x^{-1}y^{-1}xy)g^{-1} = (gx^{-1}g^{-1})(gy^{-1}g^{-1})(gxg^{-1})(gyg^{-1})$$

$$(gx^{-1}g^{-1})(gy^{-1}g^{-1})(gxg^{-1})(gyg^{-1}) = (gxg^{-1})^{-1}(gyg^{-1})^{-1}(gxg^{-1})(gyg^{-1}) \in N$$

We can prove the lemma by following:
Given $g^{-1}Sg = S$, want to show $g^{-1}S^n g$

$$g^{-1}S^n g = g^{-1}S^{n-1}Sg = g^{-1}S^{n-1}gg^{-1}Sg = g^{-1}S^{n-1}g$$

By induction, we can see that it is equivalent.
G/N is Abelian:
This is obvious given question 40. □