Abstract Algebra: Homework #8

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1 Chapter 15, Exercise A1

Suppose $G = \mathbb{Z}_{10} \wedge H = \{0, 5\}$.

Then, table 1 describes the operation table for G/H with respect to coset multiplication defined for cosets of an abelian group, denoted $*$.

I exclusively use multiplicative notation here because I like it better, but $aH \ni a \in G$ denotes the coset $a +_{10} H$. Since G is abelian, I use left and right cosets interchangably.

The following are the elements of G/H:

$$\begin{aligned}
H0 =& \{0, 5\} \\
H1 =& \{1, 6\} \\
H2 =& \{2, 7\} \\
H3 =& \{3, 8\} \\
H4 =& \{4, 9\}
\end{aligned}$$

$*$	$H0$	$H1$	$H2$	$H3$	$H4$
$H0$	$H0$	$H1$	$H2$	$H3$	$H4$
$H1$	$H1$	$H2$	$H3$	$H4$	$H0$
$H2$	$H2$	$H3$	$H4$	$H0$	$H1$
$H3$	$H3$	$H4$	$H0$	$H1$	$H2$
$H4$	$H4$	$H0$	$H1$	$H2$	$H3$

Table 1: Operation table for G/H under $*$

If we replace each HX in the table with an $\mathsf{f(HX)}$ where $\mathsf{f} : \mathsf{G/H} \to \mathbb{Z}_5 \ni \mathsf{f(HX)} = \mathsf{X}$ and replace $*$ by $+_5$, we construct the operation table for $\mathbb{Z}_5$. By table inspection, this f is an isomorphism from $\mathsf{G/H}$ to $\mathbb{Z}_5$, so clearly $\mathsf{G/H} \cong \mathbb{Z}_5$.

2 Chapter 15, Exercise A4

Denote the elements of D_4 as:

$$R_0 = \begin{pmatrix} 1 & 2 & 3 & 4 \\ 1 & 2 & 3 & 4 \end{pmatrix} \quad R_{\pi/2} = \begin{pmatrix} 1 & 2 & 3 & 4 \\ 4 & 1 & 2 & 3 \end{pmatrix} \quad R_\pi = \begin{pmatrix} 1 & 2 & 3 & 4 \\ 3 & 4 & 1 & 2 \end{pmatrix} \quad R_{3\pi/2} = \begin{pmatrix} 1 & 2 & 3 & 4 \\ 2 & 3 & 4 & 1 \end{pmatrix} \tag{1}$$

$$H = \begin{pmatrix} 1 & 2 & 3 & 4 \\ 4 & 3 & 2 & 1 \end{pmatrix} \quad V = \begin{pmatrix} 1 & 2 & 3 & 4 \\ 2 & 1 & 4 & 3 \end{pmatrix} \quad D = \begin{pmatrix} 1 & 2 & 3 & 4 \\ 3 & 2 & 1 & 4 \end{pmatrix} \quad D' = \begin{pmatrix} 1 & 2 & 3 & 4 \\ 1 & 4 & 3 & 2 \end{pmatrix} \tag{2}$$

The operation table for function composition $\circ$ on D_4 is given in table 1

$\circ$	R_0	$R_{\pi/2}$	R_π	$R_{3\pi/2}$	H	V	D	D'
R_0	R_0	$R_{\pi/2}$	R_π	$R_{3\pi/2}$	H	V	D	D'
$R_{\pi/2}$	$R_{\pi/2}$	R_π	$R_{3\pi/2}$	R_0	D'	D	H	V
R_π	R_π	$R_{3\pi/2}$	R_0	$R_{\pi/2}$	V	H	D'	D
$R_{3\pi/2}$	$R_{3\pi/2}$	R_0	$R_{\pi/2}$	R_π	D	D'	V	H
H	H	D	V	D'	R_0	R_π	$R_{\pi/2}$	$R_{3\pi/2}$
V	V	D'	H	D	R_π	R_0	$R_{3\pi/2}$	$R_{\pi/2}$
D	D	V	D'	H	$R_{3\pi/2}$	$R_{\pi/2}$	R_0	R_π
D'	D'	H	D	V	$R_{\pi/2}$	$R_{3\pi/2}$	R_π	R_0

Table 2: Operation table for D_4 under $\circ$

Now that we have better notation than Pinter, let $G = D_4 \wedge H \leq G \ni H = \{R_0, R_\pi, H, V\}$

Note that other than H, G/H contains only one other element since $(G : H) = 2$.

We can then fully describe $G/H = \Big\{\{R_0, R_\pi, H, V\}, \{R_{\pi/2}, R_{3\pi/2}, D, D'\}\Big\}$.

Table 3 give the operation table for G/H under coset multiplication:

$*$	H	HD
H	H	HD
HD	HD	H

Table 3: Operation table for G/H under coset multiplication

3 Chapter 15, Exercise C1

Suppose $H \trianglelefteq G$ where G is a group.

Theorem 1. $(\forall x \in G)(x^2 \in H) \iff (\forall X \in G/H)(X^2 = H)$

Proof. Suppose that $(\forall x \in G)(x^2 \in H)$. Let $X \in G/H$. Then, $X = Hx \ni x \in G$. Therefore, $XX = (Hx)(Hx) = H(x^2) = H$ since $x^2 \in H \implies h(x^2) \in H$ for any $h \in H$ since H is closed under the group operation. Then, $(\forall X \in G/H)(X^2 = H)$.

Conversely, suppose $(\forall X \in G/H)(X^2 = H)$. Let $x \in G$ and let $X = Hx$. Then, $X^2 == (Hx)(Hx) = Hx^2$. By assumption, $X^2 = Hx^2 = H$, and by Pinter chapter 15 theorem 5 part 2, we have $Hx^2 = H \iff x^2 \in H$.

The first implication and its converse thus proved demostrates bidirecitonal implication. This proves theorem 1. $\square$

4 Chapter 15, Exercise D1

Suppose $H \trianglelefteq G$ where G is a group.

Theorem 2. $|H| \in \mathbb{N} \wedge |G/H| \in \mathbb{N} \implies |G| \in \mathbb{N}$

Proof. Let $n = |H| \in \mathbb{N}$ and let $m = |G/H|$. Since G/H is the set of all left cosets of H with respect to G, we can write $|G/H|$ as $(G : H)$, the index of H with respect to G. By Lagrange's theorem, we have $|G| = (G : H) \cdot |H| = mn$. Since $m, n \in \mathbb{N}$ and the naturals are closed under multiplication, we must have $|G| \in \mathbb{N}$. This proves theorem 2. $\square$

5 Chapter 15, Exercise E2

Suppose $H \trianglelefteq G$ where G is a group.

Theorem 3. $m = (G : H) \implies (\forall x \in G/H)(\text{ord}(x)|m)$

Proof. Suppose $m = (G : H)$. Then, since $(G : H) = |G/H|$, we have as a consequence of Lagrange's theorem that $(\forall x \in G/H)(\text{ord}(x) \mid |G/H|)$, therefore $(\forall x \in G/H)(\text{ord}(x)|m)$. This proves theorem 3. $\square$

6 Chapter 15, Exercise E5

Suppose $H \trianglelefteq G$ where G is a group.

Theorem 4. $m = (G : H) \implies a^m \in G$ *for any* $a \in G$

Proof. Suppose $m = (G : H)$ and let $a \in G$. Then, $a^m \in G$ since G is closed under multiplication. This proves theorem 4 for some reason. $\square$

7 Chapter 15, Exercise E6

Suppose $H \trianglelefteq G$ where G is a group.

Theorem 5. $(\forall x \in \mathbb{Q}/\mathbb{Z})(\text{ord}(x) \in \mathbb{N})$

Proof. Suppose $x \in \mathbb{Q}/\mathbb{Z}$. Then x can be written as some $y+\mathbb{Z}$, where $y \in \mathbb{Q}$. Then, we can write $y = \frac{m}{n}$ for some $m, n \in \mathbb{Z}$ by the definition of $\mathbb{Q}$. We want to find an $n \in \mathbb{N}$ such that $n(y+\mathbb{Z}) = \mathbb{Z}$. Any $n(y+\mathbb{Z})$ is just $(ny+\mathbb{Z})$, however this n is no aribtrary integer, it is in fact the same n we see in the denominator of $y = \frac{m}{n}$, for then $(ny + \mathbb{Z}) = (n\frac{m}{n} = \mathbb{Z}) = (m + \mathbb{Z})$, and since $m \in \mathbb{Z}$, we have $m + \mathbb{Z} = \mathbb{Z}$, and every $x \in \mathbb{Q}/\mathbb{Z}$ satisfies $n(y + \mathbb{Z}) = \mathbb{Z}$ for any $y = \frac{m}{n} \in \mathbb{Q}$, therefore $\text{ord}(x) = n \in \mathbb{N}$. This proves theorem 5. $\square$

8 The elements of factor group form an equivalence class

Define the equivalence relation $\sim$ by $r \sim s \iff r - s \in \mathbb{Z}$ for some $r, s \in \mathbb{Q}$. Let $[r]$ refer to the equivalence class of r with respect to $\sim$.

Theorem 6. $\mathbb{Q}/\mathbb{Z} = \{X : X = [r] \ni r \in \mathbb{Q}\}$.

Proof. Suppose $X \in \mathbb{Q}/\mathbb{Z}$. Then, X is a coset of the form $r + \mathbb{Z}$ where $r \in \mathbb{Q}$. Let $a, b \in X$. Then, $a = r + x_1 \ni x_1 \in \mathbb{Z}$ and $b = r + x_2 \ni x_2 \in \mathbb{Z}$. Therefore,

$a - b = (r + x_1) - (r + x_2) = x_1 - x_2 \in \mathbb{Z} \iff a \sim b \iff X = [r]$, therefore any $a, b \in X \implies a \sim b$, so any $X \in \mathbb{Q}/\mathbb{Z} \implies X = [r] \ni r \in \mathbb{Q}$.

Conversely, suppose $X = [r] \ni r \in \mathbb{Q}$. Then, any $a, b \in X$ can be written as $r + x_1 \ni x_1 \in \mathbb{Z}$. This is exactly the definition of a coset of the integers under the rationals, so we must have $X \in \mathbb{Q}/\mathbb{Z}$. Then, $X \in \mathbb{Q}/\mathbb{Z} \implies X = [r] \ni r \in \mathbb{Q} \wedge X = [r] \ni r \in \mathbb{Q} \implies X \in \mathbb{Q}/\mathbb{Z} \iff \mathbb{Q}/\mathbb{Z} = \{X : X = [r] \ni r \in \mathbb{Q}\}$ by the axiom of extentionality. This proves theorem 6. $\square$

9 Factoring the alternating group of four elements

Suppose $H = \{e, (12)(34), (13)(24), (14)(23)\}$ is a subgroup of the $A_4 = \{e, (12)(34), (13)(24), (14)(23), (123), (132), (124), (142), (134), (143), (234), (243)\}$ alternating group of four elements. In fact $H \trianglelefteq A_4$ by Homework 7 problem 12.

Then, we can write $A_4/H = \{H, H(123), H(132)\}$, and table 4 gives the operation table for A_4/H under coset multiplication.

$*$	H	$H(123)$	$H(132)$
H	H	$H(123)$	$H(132)$
$H(123)$	$H(123)$	$H(132)$	H
$H(132)$	$H(132)$	H	$H(123)$

Table 4: Operation table for A_4/H under coset multiplication

Theorem 7. $Ha \in A_4/H \ni a \notin H \implies \text{ord}(Ha) = 3$.

Proof. This is a simple proof by exhaustion. There are only two cases to check. First, observe that $(H(123))^2 = H(123)^2 = H(132)$, and $(H(123))^3 = H(132) \cdot H(123) = H((132)(123)) = H$, so $\text{ord}(H(123)) = 3$. Then, observe that $(H(132))^2 = H(132)^2 = H(123)$, and $(H(132))^3 = H(123) \cdot H(132) = H((123)(132)) = H$, so $\text{ord}(H(132)) = 3$. Since there are no other unique cosets where $a \notin H$, we have shown that theorem 7 holds for all possible cases, so this proves theorem 7 in general. $\square$

10 Digging up an old equivalence relation

Suppose $\mathsf{f}, \mathsf{g} \in \mathcal{F}(\mathbb{R})$.

Suppose we have the function $\phi : \mathcal{D}(\mathbb{R}) \to \mathcal{F}(\mathbb{R})$ defined by $\phi(\mathsf{f}) = \frac{df}{dx}$ where x is the independent variable of f. By the result of Homework 7 problem 2, ϕ is an epimorphism from $\mathcal{D}(\mathbb{R})$ to $\mathcal{F}(\mathbb{R})$, so ϕ is a homomorphism from $\mathcal{D}(\mathbb{R})$ to $\mathcal{F}(\mathbb{R})$. Let $\mathsf{H} = \ker(\phi)$ and define the relation $\sim$ as:

$$\mathsf{f} \sim \mathsf{g} \iff (\forall x \in \mathbb{R})(\mathsf{f}(x) - \mathsf{g}(x) = c \text{ for some } c \in \mathbb{R}) \tag{3}$$

Theorem 8. $(\forall \mathsf{f} \in \mathcal{D}(\mathbb{R}))(\mathsf{f} + \mathsf{H} = \{\mathsf{g} \in \mathcal{D}(\mathbb{R}) : \mathsf{g} = \mathsf{f} + c \ni c \in \mathbb{R}\})$

Proof. Suppose $\mathsf{f} \in \mathcal{D}(\mathbb{R})$. Then, $[\mathsf{f}] = \{\mathsf{g} \in \mathcal{D}(\mathbb{R}) : \mathsf{g} \sim \mathsf{f}\}$, and let $\mathsf{g} \in [\mathsf{f}]$. $\mathsf{f} \sim \mathsf{g} \iff (\forall x \in \mathbb{R})(\mathsf{f}(x) - \mathsf{g}(x) = c \ni c \in \mathbb{R})$. Since the neutral element of $\mathcal{F}(\mathbb{R})$ is $\epsilon(x) = 0$ and only a $c \in \mathbb{R}$ satisfies $\frac{d}{dx}x = 0$, we can describe H entirely by $\mathsf{H} = \mathbb{R}$, so clearly every $\mathsf{g} \in [\mathsf{f}]$ satisfies $\mathsf{g} = \mathsf{f} + c$ and this is exactly the definition of g being an element of the coset $\mathsf{f} + \mathsf{H}$, so any $\mathsf{g} \in [\mathsf{f}]$ satisfies $\mathsf{g} \in \mathsf{f} + \mathsf{H}$. In fact, it works both ways, that any $\mathsf{g} \in \mathsf{f} + \mathsf{H}$ can be written as some $\mathsf{g} = \mathsf{f} + c \ni c \in \mathbb{R}$, so $\mathsf{g} - \mathsf{f} = c \in \mathbb{R}$, implicitly, for any value of the independent variable of the two functions. This is exactly the definition that $\mathsf{f} \sim \mathsf{g}$, so we have $\mathsf{g} \in [\mathsf{f}]$, and by the axiom of extensionality we must have $\mathsf{f} + \mathsf{H} = \{\mathsf{g} \in \mathcal{D}(\mathbb{R}) : \mathsf{g} = \mathsf{f} + c \ni c \in \mathbb{R}\}$ for any $\mathsf{f} \in \mathcal{D}(\mathbb{R})$. This proves theorem 8. $\square$

11 A homomorphism on continuous functions

Suppose $\mathsf{G} = \mathcal{C}(\mathbb{R})$ and define $\psi : \mathsf{G} \to \mathbb{R} \ni \psi(\mathsf{f}) = \int_0^1 \mathsf{f}(x)dx$. We consider the group G under function addition and the group of the real numbers under conventional addition.

Theorem 9. ψ *is a homomorphism with kernel* $\ker(\psi) = \mathsf{H} = \{\mathsf{f} \in \mathcal{C}(\mathbb{R}) : \int_0^1 \mathsf{f}(x)dx = 0 \in \mathbb{R}\}$.

Proof. Let $\mathsf{f}, \mathsf{g} \in \mathcal{C}(\mathbb{R})$. Then, $\psi(\mathsf{f} + \mathsf{g}) = \int_0^1(\mathsf{f}(x) + \mathsf{g}(x)dx = \int_0^1 \mathsf{f}(x)dx + \int_0^1 \mathsf{g}(x)dx = \psi(\mathsf{f})\psi(\mathsf{g})$, so ψ is a homomorphism. Since the additive identity of $\mathbb{R}$ is 0 and any for any $\mathsf{f} \in \mathcal{C}(\mathbb{R})$, we have $\psi(\mathsf{f}) = \int_0^1 \mathsf{f}(x)dx$, we can fully describe the kernel of ψ by $\ker(\psi) = \{\mathsf{f} \in \mathcal{C}(\mathbb{R}) : \int_0^1 \mathsf{f}(x)dx = 0 \in \mathbb{R}\}$. This proves theorem 9. $\square$

By theorem 9, G/H is defined since the kernel of a homomorphism is a normal subgroup of the domain of that same homomorphism. Then, we can descibe this quotient group by $G/H = \{X : X = f + H \ni (\forall g \in H)(\int_0^1 (f(x) + g(x))dx = \int_0^1 g(x)dx)\}$.

12 Normal subgroups of the general linear group in two dimensions

Suppose $G = GL_2(\mathbb{R})$ and $H = \{X \in G : \det(X) = 1\} = SL_2(\mathbb{R})$ be a subgroup of G.

Theorem 10. $H \trianglelefteq G$

Proof. Define the function $\phi : GL_2(\mathbb{R}) \to \mathbb{R}^* \ni \phi(A) = \det(A) \ni A \in GL_2(\mathbb{R})$. Then every $X \in GL_2(\mathbb{R})$ satisfies $\phi(X) = \det(X) = 1 \iff X \in SL_2(\mathbb{R})$ because this is exactly the definition of an element being in $SL_2(\mathbb{R})$. Since for any $A, B \in GL_2(\mathbb{R})$, we have $\phi(AB) = \det(AB) = \det(A)\det(B) = \phi(A)\phi(B)$, we have that ϕ is a homomorphism from $GL_2(\mathbb{R})$ to $\mathbb{R}^*$ with $\ker(\phi) = SL_2(\mathbb{R})$. Then, since the kernel of a homomorphism is a normal subgroup of the domain, we have that $SL_2(\mathbb{R})$ is a normal subgroup of $GL_2(\mathbb{R})$, that is to say, $H \trianglelefteq G$ and this proves theorem 10. $\square$