P1

Proof:

1. First, prove the relation to be equivalent:
   - Reflective: $a \sim a \Rightarrow f(a) = f(a)$, TRUE.
   - Symmetric: $a \sim b \Rightarrow f(a) = f(b) \Rightarrow f(b) = f(a) \Rightarrow b \sim a$, TRUE.
   - transitive: $a \sim b, b \sim c \Rightarrow f(a) = f(b), f(b) = f(c) \Rightarrow f(a) = f(c) \Rightarrow a \sim c$, TRUE.
2. Then, prove its equivalence classes to be the fibers of f:

   Let C be the set of equivalence classes of A under $\sim$, and let F be the set of fibers of f. We will show that $C = F$.

   Take an arbitrary element $a \in A$. The equivalence class of $a \in A$ is:

$$\begin{aligned} \{x \in A \mid x \sim a\} &= \{x \in A \mid f(x) = f(a)\} \\ &= f^{-1}\{f(a)\} \end{aligned} \tag{1}$$

   which by definition is the fiber of f.

   Since a was arbitrary, every equivalence class is a fiber of f, i.e. $C \subseteq F$.

   Conversely, let F' be an arbitrary fiber of f for some $b \in B$. Then by definition,

$$\begin{aligned} F' &= f^{-1}\{b\} \\ &= \{x \in A \mid f(x) = b\} \end{aligned} \tag{2}$$

   .

   Since f is surjective, $\exists a \in A \ s.t. \ f(a) = b$. Consider the equivalence class of a:

$$\begin{aligned} \{x \in A \mid x \sim a\} &= \{x \in A \mid f(x) = f(a)\} \\ &= \{x \in A \mid f(x) = b\} \\ &= F'. \end{aligned} \tag{3}$$

   Since F' was arbitrary, every fiber of f is an equivalence class, i.e. $F \subseteq C$. Thus, $C = F$. ■

P2

Prove by contradiction:

1. Consider an arbitrary **column** in the multiplication table of G. Suppose that the colum is *not* a permutation of G.

   Then there would be at least two identical elements in this column, which we denote as a . This implies that

   $$\exists x, y \in G, x \neq y, s.t.\ xa = ya \tag{4}$$

   Applying x^{-1} from right on both sides:

   $$\begin{aligned} x^{-1}xa &= x^{-1}ya \\ a &= x^{-1}ya \\ \Rightarrow x^{-1}y &= e. \end{aligned} \tag{5}$$

   Since inverse of an element is unique, $y = x$, which is a contradiction.

2. Similarly, consider arbitrary **row** in the multiplication table of G . Suppose that this row is *not* a permutation of G , i.e. there are at least two repeating elements, denoted as b. This implies

   $$\exists x, y \in G, x \neq y, s.t.\ xa = xb. \tag{6}$$

   Applying a^{-1} from left on both sides:

   $$\begin{aligned} xaa^{-1} &= xba^{-1} \\ x &= xba^{-1} \\ \Rightarrow ba^{-1} &= e. \end{aligned} \tag{7}$$

   Since inverse of an element is unique, $b = a$, a contradiction. ■

3. Multiplication tables are special cases of Latin squares. In particular, they hold hold the property of associativity. This restricts the set of possible Latin squares, because:

   The group operation must be associative, menaing for every single combiniation of three elements, $a, b, c \in G, (ab)c = a(bc)$.

   In a table, this means:

   - let entry $(a, b) := d$ and entry $(d, c) := e$, then we must have entry (d, c) equal to entry (a, e).

   This is a strong restriction on the possible arrangements of elements in a Latin square, and thus only a small subset of Latin squares can be multiplication tables of groups.

P3

We check each axiom one by one:

Closure: Satisfied.

For any $a, b \in \mathbb{R}, a + b \in \mathbb{R}_{\text{ext}}$.
If at least one of the numbers is ∞, the sum is $\infty \in \mathbb{R}_{\text{ext}}$.

associativity: Satisfied.

We want to show that for any $a, b, c \in \mathbb{R}_{\text{ext}}, (a + b) + c = a + (b + c)$. We have two cases:

- If all elements are real, then the sum is trivially associative.
- If at least one element is ∞, then both sides equal ∞.

Identity: Satisfied.

The identity element is $0 \in \mathbb{R}_{\text{ext}}$. For any $a \in \mathbb{R}_{\text{ext}}, a + 0 = 0 + a = a$.

Inverse: NOT satisfied.

Assume not, then for $\infty \in \mathbb{R}_{\text{ext}}, \exists a \in \mathbb{R}_{\text{ext}} s.t. a + \infty = 0$. This is a contradiction, since $a + \infty = \infty$ for any $a \in \mathbb{R}_{\text{ext}}$.

Therefore, $(\mathbb{R}_{\text{ext}}, +)$ is not a group. ■

P4

$$G = \{z \in \mathbb{C} \mid z^n = 1 \text{ for some } n \in \mathbb{Z}^+\} \tag{8}$$

a. Prove that G is a group under multiplication.

We check for each axiom:

Closure:

let $a, b \in G$, then $a^{n_1} = 1, b^{n_2} = 1$, for some $n_1, n_2 \in \mathbb{Z}^+$. Need to show that $ab \in G \Leftrightarrow (ab)^k = 1$ for some $k \in \mathbb{Z}^+$.
Take $k = n_1 n_2$, then

$$(ab)^k = a^{n_1 n_2} b^{n_1 n_2} = 1^{n_2} 1^{n_1} = 1. \tag{9}$$

Exists such k, and so $ab \in G$, i.e. closure is satisfied.

Assoc.

Taivially satisfied, as $G \subset \mathbb{C}$, each element is a complex number, and multiplication of complex numbers is associative.

Identity.

Trivially satisfied, as $1 \in G$ (take $n = 1$), and for any $a \in G, a1 = 1a = a$.

Inverse.

Consider arbitrary $a \in G$. Exists $n \in \mathbb{Z}^+ \ s.t. \ a^n = 1$. Rewriting,

$$a^{n-1} a = 1 \Rightarrow a^{n-1} = a^{-1}. \tag{10}$$

Since $\left(z^{n-1}\right)^n = (z^n)^{n-1} = 1$, $z^{n-1} \in G$.

Therefore, $(G, \times)$ is a group. ■

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b. $(G, +)$ is not a group.

Assume identity exists, then for any $a \in G$,

$$e + a = a + e = a. \tag{11}$$

Since $a, e \in \mathbb{C}$, the identity must be 0. However, $0 \notin G$, since $0^n = 0$ for any $n \in \mathbb{Z}^+$, a contradiction. Thus the identity axiom is failed. ■

P5
We check the four axioms:

Clousure:
As given in the problem, H is closed under $\star$.

Associativity:
Since $H \subset G$ and $\star$ is associative on G, $\star$ is also associative on H.

Inverse:
We are given that H is closed under inverse, and so the inverse axiom is satisfied.

Identity:
Since H is nonempty, take arbitrary $h \in H$. Since H is closed under inverse, $h^{-1} \in H$. Now, we have:

$$h \star h^{-1} = h^{-1} \star h \coloneqq e. \tag{12}$$

This identity element must exist in H by closure of H under $\star$. Thus, the identity axiom is satisfied.

P6

$(A, \star)$ and $(B, \diamondsuit)$ are groups. $A \times B := \{(a, b) \mid a \in A, b \in B\}$ with operation:$(a, b)(c, d) = (a \star c, b \diamondsuit d)$ for all $(a, b), (c, d) \in A \times B$.

1. Check group axioms:

Closure:

Take arbitrary (a_1, b_1) and $(a_2, b_2) \in A \times B$. Then,

$$(a_1, b_1)(a_2, b_2) = (a_1 \star a_2, b_1 \diamondsuit b_2). \tag{13}$$

Since A and B are groups, $a_1 \star a_2 \in A$ and $b_1 \diamondsuit b_2 \in B$. Thus, $(a_1 \star a_2, b_1 \diamondsuit b_2) \in A \times B$, i.e. closure is satisfied.

Associativity:

Take arbitrary $(a_1, b_1), (a_2, b_2), (a_3, b_3) \in A \times B$. Then,

$$\begin{aligned}
[(a_1 \, , b_1)(a_2 \, , b_2)](a_3 \, , b_3) &= (a_1 \star a_2 \, , b_1 \diamondsuit b_2)(a_3 \, , b_3) \\
&= ((a_1 \star a_2) \star a_3 \, , (b_1 \diamondsuit b_2) \diamondsuit b_3) \\
&= (a_1 \star (a_2 \star a_3) \, , b_1 \diamondsuit (b_2 \diamondsuit b_3)) \\
&= (a_1 \, , b_1)(a_2 \star a_3 \, , b_2 \diamondsuit b_3) \\
&= (a_1 \, , b_1)[(a_2 \, , b_2)(a_3 \, , b_3)].
\end{aligned} \tag{14}$$

and so associativity is satisfied.

Identity:

Take arbitrary $(a, b) \in A \times B$. Let e_A and e_B be the identity elements of A and B respectively. Then,

$$(a, b)(e_A, e_B) = (a \star e_A, b \diamondsuit e_B) = (a, b) \tag{15}$$

and similarly, $(e_A, e_B)(a, b) = (e_A \star a, e_B \diamondsuit b) = (a, b)$. Thus, the identity axiom is satisfied with identity element (e_A, e_B).

Inverse:

Take arbitrary $(a, b) \in A \times B$. Let a^{-1} and b^{-1} be the inverses of a and b in A and B respectively. Then,

$$(a, b)(a^{-1}, b^{-1}) = (a \star a^{-1}, b \diamondsuit b^{-1}) = (e_A, e_B). \tag{16}$$

Similarly, $(a^{-1}, b^{-1})(a, b) = (e_A, e_B)$ and so the inverse axiom is satisfied. ■

2. Prove that $A \times B$ is abelian iff both $(A, \star)$ and $(B, \diamondsuit)$ are abelian.

$\Longrightarrow$: Assume $A \times B$ is abelian, then for any $a_1, a_2 \in A$ and $b_1, b_2 \in B$, we have:

$$(a_1, b_1)(a_2, b_2) = (a_2, b_2)(a_1, b_1). \tag{17}$$

LHS:

$$(a_1, b_1)(a_2, b_2) = (a_1 \star a_2, b_1 \diamondsuit b_2). \tag{18}$$

RHS:

$$(a_2, b_2)(a_1, b_1) = (a_2 \star a_1, b_2 \diamondsuit b_1). \tag{19}$$

Thus $a_1 \star a_2 = a_2 \star a_1$ and $b_1 \diamondsuit b_2 = b_2 \diamondsuit b_1$, and so A and B are abelian.

$\Longleftarrow$: Assume both $(A, \star)$ and $(B, \diamondsuit)$ are abelian, then for any $a_1, a_2 \in A$ and $b_1, b_2 \in B$, we have:

$$(a_1, b_1)(a_2, b_2) = (a_1 \star a_2, b_1 \diamondsuit b_2) = (a_2 \star a_1, b_2 \diamondsuit b_1) = (a_2, b_2)(a_1, b_1). \tag{20}$$

This shows that $A \times B$ is abelian. ■

P7

1. Prove that $xy = yx$ iff $y^{-1}xy = x$ iff $x^{-1}y^{-1}xy = 1$.

- Start from left.

Suppose $xy = yx$, applying y^{-1} on both sides gives $y^{-1}xy = y^{-1}yx = x$.

Conversely, suppose $y^{-1}xy = x$, then $yy^{-1}xy = yx \Rightarrow xy = yx$. The first equivalence is proved.

- Now suppose $y^{-1}xy = x$. Applying x^{-1} on both sides gives $x^{-1}y^{-1}xy = x^{-1}x = 1$.
  Conversely, suppose $x^{-1}y^{-1}xy = 1$. Applying x on both sides gives $xx^{-1}y^{-1}xy = x \Rightarrow y^{-1}xy = x$. The second equivalence is proved, thus completing the proof. ■

2. Prove further that $|yxy^{-1}| = |x|$.

Let $|x| = n$ and $|yxy^{-1} = m$

- First, prove that $m \leq n$: Since $x^n = e$, expanding (yxy^{-1}) :

$$\begin{aligned} yxy^{-1}yxy^{-1}...yxy^{-1}(n\,\times) &= yx^ny^{-1} \\ &= yey^{-1} \\ &= e. \end{aligned} \tag{21}$$

  And so m divides n, i.e. $m \leq n$.

- Then, prove that $n \leq m$: Since $(yxy^{-1})^m = e$,expanding $(yxy^{-1})^m$ in the same way gives

$$yx^my^{-1} = e \Rightarrow y^{-1}x^my^{-1}y = e \Rightarrow x^m = e \tag{22}$$

  and so n divides m, i.e. $n \leq m$.

Thus we have $m = n$, i.e. $|yxy^{-1}| = |x|$. ■

3. Prove that $|xy| = |yx|\ \forall x, y \in G$.

From part 2, we know that for any $g, h \in G$, $|g| = |hgh^{-1}|$. Now let $g = xy$ and $h = x^{-1}$, then we can show:

$$|xy| = |x^{-1}(xy)(x^{-1})^{-1}| = |x^{-1}xyx| = |yx| \tag{23}$$

Thus $|xy| = |yx|\ \forall x, y \in G$. ■

P8

As hinted, $t(G) = \{g \in G \mid g \neq g^{-1}\}$. Consider any $g \in t(G)$, then $g^{-1} \in t(G)$ as well.
This implies that g and $g^{-1}$are distinct, and so $t(G)$ is composed of pairs of elements, and so $|t(G)|$ is even.
Since $|G|$ is also even, $|G| - |t(G)|$ is even.

Now, $G - t(G)$ is nonempty since the identity $e \notin t(G)$. Thus exists

$$a \neq e \; s.t. \; a \in G - t(G). \tag{24}$$

We choose $a \notin t(G)$, then $a = a^{-1}$ so that $a^2 = e, a \neq e$. This implies that a is an element of order 2. ■