

# Abstract Algebra

G. V. V. Sharma

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## 1 THINGS FAMILIAR AND LESS FAMILIAR

### 1.1 Introduction

- let  $S$  be a set having an operation  $*$  which assigns an element  $a*b$  of  $S$  for any  $a, b \in S$ . Let us assume that the following two rules hold:
  - If  $a, b$  are any objects in  $S$ , then  $a*b = a$ .
  - If  $a, b$  are any objects in  $S$ , then  $a*b = b*a$ .

Show that  $S$  can have at most one object.

**Solution:** From condition 1.1.1a, interchanging  $a, b$ ,

$$b*a = b \quad (1.1.1)$$

and from condition 1.1.1b,

$$b*a = a*b \quad (1.1.1)$$

But from condition 1.1.1a,

$$a*b = a \implies a = b \quad (1.1.1)$$

Thus,  $S$  can have at most one object.

- Let  $S$  be the set of all integers  $0, \pm 1, \pm 2, \dots, \pm n, \dots$ . For  $a, b \in S$ , define  $*$  by

$$a*b = a - b \quad (1.1.2)$$

Verify the following

- $a*b \neq b*a$  unless  $a = b$
- $(a*b)*c \neq a*(b*c)$  in general. Under what conditions on  $a, b, c$  is

$$(a*b)*c \neq a*(b*c) \quad ? \quad (1.1.2)$$

- The integer  $a$  has the property that  $a*0 = a$  for every  $a \in S$ .
- For  $a \in S, a*a = 0$ .

**Solution:**

a)

$$a*b = b*a \quad (1.1.2)$$

$$\implies a - b = b - a \quad (1.1.2)$$

$$\text{or, } a = b \quad (1.1.2)$$

- Let  $a = 1, b = 2, c = 4$ . Then,

$$a*b = -1, (a*b)*c = -1 - 4 = -5 \quad (1.1.2)$$

$$b*c = -2, a*(b*c) = 1 + 2 = 3 \neq -5 \quad (1.1.2)$$

Thus, for the given condition to be satisfied,

$$(a - b) - c = a - (b - c) \quad (1.1.2)$$

$$\implies c = 0 \quad (1.1.2)$$

c)

$$a*0 = a - 0 = a \quad (1.1.2)$$

d)

$$a*a = a - a = 0 \quad (1.1.2)$$

- Let  $S$  consist of the two objects  $\square$  and  $\triangle$ . We define the operation  $*$  on  $S$  by subjecting  $\square$  and  $\triangle$  to the following conditions.

$$\text{a) } \square * \triangle = \triangle = \triangle * \square$$

$$\text{b) } \square * \square = \square$$

$$\text{c) } \triangle * \triangle = \square$$

Verify by explicit calculation that if  $a, b, c$  are any elements of  $S$ , (i.e.  $a, b, c$  can be any of  $\square$  or  $\triangle$ ), then

- a)  $a * b$  is in  $S$
- b)  $(a * b) * c = a * (b * c)$
- c)  $a * b = b * a$
- d) There is a particular  $a$  in  $S$  such that  $a * b = b * a = b$  for all  $b \in S$
- e) Given  $b \in S, b * b = a$ , where  $a$  is the particular element in Part 1.1.3d.

**Solution:** Let  $\square = 1, \triangle = -1$ . These satisfy all the given conditions.

- a)  $a * b \in [1, -1] \in S$ .
- b) Writing the truth table,  $(a * b) * c = a * (b * c)$ .
- c)  $a * b = b * a$  can be verified by writing the truth table.
- d) For  $a = 1, a * b = b * a = b$ , for all  $b \in S$ .
- e) For  $a = 1$ , if  $b = -1, b * b = 1 = a$ . This can be shown to be true for  $b = 1$  as well.

## 1.2 Set Theory

1. Describe the following sets verbally

- a)  $S = \{\text{Mercury, Venus, Earth, } \dots, \text{Pluto}\}$
- b)  $S = \{\text{Andhra Pradesh, Uttar Pradesh, } \dots, \text{Assam}\}$

**Solution:**

- a) Planets
- b) Indian states

2. Describe the following sets verbally

- a)  $S = \{2, 4, 6, 8, \dots\}$
- b)  $S = \{2, 4, 8, 16, \dots\}$
- c)  $S = \{1, 4, 9, 16, 25, 36, \dots\}$

**Solution:**

- a) Even numbers
- b) Powers of 2
- c) Squares of positive integers

3. If  $A$  is the set of all residents of India,  $B$  the set of all Sri Lankan citizens, and  $C$  the set of all women in the world, describe the sets  $ABC, A - B, A - C, C - A$  verbally.

**Solution:**

- a)  $ABC$  is the set of all women residents of India who are citizens of Sri Lanka.
- b)  $A - B = AB'$  is the set of all residents of India who are not Sri Lankan citizens.
- c)  $A - C = AC'$  is the set of all male residents of India.
- d)  $C - A = CA'$  is the set of all women who are not residing in India.

4. If  $A = \{1, 4, 7, a\}$  and  $B = \{3, 4, 9, 11\}$  and you have been told that  $AB = \{4, 9\}$ , then what must

$a$  be?

**Solution:**  $a = 9$

5. If  $A \subset B, B \subset C$ , prove that  $A \subset C$

**Solution:** From the given information,

$$A + P = B, AP = 0, B + Q = C, BQ = 0 \quad (1.2.5.1)$$

$$\implies B + Q = A + P + Q = C, \quad (1.2.5.2)$$

$$\therefore BQ = 0,$$

$$AQ + PQ = 0 \implies AQ = 0, PQ = 0 \quad (1.2.5.3)$$

Hence,

$$A(P + Q) = 0 \implies A \subset C \quad (1.2.5.4)$$

6. If  $A \subset B$  prove that  $A \cup C \subset B \cup C$  for any set  $C$ .

**Solution:** From the given information, there exists  $P$  such that

$$A + P = B, AP = 0 \quad (1.2.6.1)$$

Also,

$$B + C = A + P + C \quad (1.2.6.2)$$

$$\implies A + C \subset B + C \quad (1.2.6.3)$$

7. Show that

$$A \cup B = B \cup A \quad (1.2.7.1)$$

$$A \cap B = B \cap A \quad (1.2.7.2)$$

8. Prove that

$$(A - B) \cup (B - A) = (A \cup B) - (A \cap B) \quad (1.2.8.1)$$

**Solution:** Since

$$A - B = AB', \quad (1.2.8.2)$$

$$(A - B) \cup (B - A) = AB' + BA' \quad (1.2.8.3)$$

Also,

$$(A \cup B) - (A \cap B) = (A + B)(AB')' \quad (1.2.8.4)$$

$$= (A + B)(A' + B') \quad (1.2.8.5)$$

$$= AB' + BA' \quad (1.2.8.6)$$

9. Prove that

$$(A) \cap (B \cup C) = (A \cap B) \cup (A \cap C) \quad (1.2.9.1)$$

**Solution:**

$$LHS = A(B + C) = AB + AC = RHS \quad (1.2.9.2)$$

10. Prove that

$$(A) \cup (B \cap C) = (A \cup B) \cap (A \cup C) \quad (1.2.10.1)$$

**Solution:**

$$LHS = A + BC \quad (1.2.10.2)$$

$$RHS = (A + B)(A + C) \quad (1.2.10.3)$$

$$= A + A(B + C) + BC \quad (1.2.10.4)$$

$$= A(1 + B + C) + BC \quad (1.2.10.5)$$

$$= LHS \quad (1.2.10.6)$$

11. Write down all the subsets of  $S = \{1, 2, 3, 4\}$ .

**Solution:** Write a program for this.

12. If  $C$  is a subset of  $S$ , let  $C'$  denote the complement of  $C$  in  $S$ . Prove the *De Morgan Rules* for subsets  $A, B$  of  $S$ , namely,

a)  $(A \cup B)' = A' \cap B'$

b)  $(A \cap B)' = A' \cup B'$

**Solution:**

a)

$$(A + B)A'B' = AA'B' + BA'B' \quad (1.2.12.1)$$

$$= 0 \quad (1.2.12.2)$$

b) Substituting  $A = A', B = B'$  in the above, the second result is obtained.

13. Let  $S$  be a set. For any two subsets of  $S$ , we define

$$A \oplus B = (A - B) \cup (B \cup A) \quad (1.2.13.1)$$

Prove that

a)  $A \oplus B = B \oplus A$ .

b)  $A \oplus \Phi = A$ .

c)  $A \cdot A = A$ .

d)  $A \oplus A = \Phi$ .

e)  $A \oplus (B \oplus C) = (A \oplus B) \oplus C$ .

f) If  $A \oplus B = A \oplus C$ , then  $B = C$ .

g)  $A \cdot (B + C) = A \cdot B + A \cdot C$ .

**Solution:** All can be proved using boolean logic.

14. If  $C$  is a finite set, let  $m(C)$  denote the number of elements in  $C$ . If  $A, B$  are finite sets, prove that

$$m(A \cup B) = m(A) + m(B) - m(A \cap B) \quad (1.2.14.1)$$

**Solution:**

$$A'B' = (A + B)' \quad (1.2.14.2)$$

$$\implies m(A'B') = m((A + B)') \quad (1.2.14.3)$$

$$= 1 - m(A + B) \quad (1.2.14.4)$$

$$\because A + B = A(B + B') + B \quad (1.2.14.5)$$

$$= B(A + 1) + AB' \quad (1.2.14.6)$$

$$= B + AB' \quad (1.2.14.7)$$

$$\implies m(A + B) = m(B + AB') \quad (1.2.14.8)$$

$$= m(B) + m(AB') \quad (1.2.14.9)$$

$$\because B(AB') = 0 \quad (1.2.14.10)$$

$$A = A(B + B') = AB + AB' \quad (1.2.14.11)$$

and

$$(AB)(AB') = 0, \because BB' = 0 \quad (1.2.14.12)$$

Hence,  $AB$  and  $AB'$  are mutually exclusive and

$$m(A) = m(AB) + m(AB') \quad (1.2.14.13)$$

$$\implies m(AB') = m(A) - m(AB) \quad (1.2.14.14)$$

Substituting (1.2.14.14) in (1.2.14.10),

$$m(A + B) = m(A) + m(B) - m(AB) \quad (1.2.14.15)$$

15. For three finite sets  $A, B, C$ , find a formula for  $m(A \cup B \cup C)$ . **Solution:** Extend the above.

16. Take a shot at finding  $m(\bigcup_{i=1}^n A_i)$ .

17. Show that if 80% of all Indians have gone to high school and 70% of all Indians read a daily newspaper, then *at least* 50% of all Indians have both gone to high school and read a daily newspaper.

**Solution:** Let  $A$  represent high school and  $B$  represent newspaper. Then,

$$\Pr(AB) = \Pr(A) + \Pr(B) - \Pr(A + B) \quad (1.2.17.1)$$

Since

$$\Pr(A + B) \leq 1, \quad (1.2.17.2)$$

$$\Pr(A) + \Pr(B) - \Pr(A + B) \geq \Pr(A) + \Pr(B) - 1 \quad (1.2.17.3)$$

$$\implies \Pr(AB) \geq 0.8 + 0.7 - 1 \quad (1.2.17.4)$$

$$= 0.5 \quad (1.2.17.5)$$

18. A public opinion poll shows that 90% of the population agreed with the government on the first decision, 84% on the second, and 74% on the third, for three decisions made by the government. At least what percentage of the population agreed with the government on all three decisions.

**Solution:** Let the decisions be  $A, B, C$ . Then,

$$\Pr(AB) \geq \Pr(ABC), \quad (1.2.18.1)$$

$$\Pr(BC) \geq \Pr(ABC), \quad (1.2.18.2)$$

$$\Pr(CA) \geq \Pr(ABC) \quad (1.2.18.3)$$

Since

$$\begin{aligned} \Pr(A + B + C) &= \sum \Pr(A) \\ &\quad - \sum \Pr(AB) + \Pr(ABC), \\ \Rightarrow \Pr(A + B + C) + \sum \Pr(AB) \\ &= \sum \Pr(A) + \Pr(ABC), \end{aligned} \quad (1.2.18.4)$$

from (1.2.18.1),

$$\begin{aligned} \Pr(A + B + C) + 3\Pr(ABC) \\ &\geq \sum \Pr(A) + \Pr(ABC), \\ \Rightarrow 2\Pr(ABC) &\geq \sum \Pr(A) - \Pr(A + B + C) \end{aligned} \quad (1.2.18.5)$$

Since

$$\Pr(A + B + C) \leq 1, \quad (1.2.18.6)$$

$$-\Pr(A + B + C) \geq -1 \quad (1.2.18.7)$$

$$\Rightarrow 2\Pr(ABC) \geq \sum \Pr(A) - 1 \quad (1.2.18.8)$$

$$\text{or } \Pr(ABC) \geq \frac{\sum \Pr(A) - 1}{2} \quad (1.2.18.9)$$

$$= 0.74 \quad (1.2.18.10)$$

19. In his book *A Tangled Tale*, Lewis Carroll proposed the following riddle about a group of disabled veterans. "Say that 70% have lost an eye, 75% an ear, 80% an arm, 85% a leg. What percentage, at least, must have lost all four?" Solve Lewis Carroll's problem.

**Solution:** Let  $A_i$  represent the events. Then,

$$\begin{aligned} \Pr\left(\sum_{i=1}^4 A_i\right) &= \sum_{i=1}^4 \Pr(A_i) - \sum_{i,j} \Pr(A_i A_j) \\ &\quad + \sum_{i,j,k} \Pr(A_i A_j A_k) - \Pr\left(\prod_{i=1}^4 A_i\right) \end{aligned} \quad (1.2.19.1)$$

Now,

$$\Pr(A_1 A_2) \geq \Pr(A_1 A_2 A_3) \geq \Pr(A_1 A_2 A_3 A_4) \quad (1.2.19.2)$$

which, upon substitution in (1.2.19.1) yields

$$\Pr\left(\sum_{i=1}^4 A_i\right) \geq \frac{\sum_{i=1}^4 \Pr(A_i) - 1}{1 + {}^4C_2 - {}^4C_3} \quad (1.2.19.3)$$

$$= 70\% \quad (1.2.19.4)$$

20. Show, for finite sets  $A, B$ , that  $m(A \times B) = m(A) \times m(B)$ .

**Solution:** Basic principle of counting.

21. If  $S$  is a set having five elements,  
 a) How many subsets does  $S$  have?  
 b) How many subsets having four elements does  $S$  have?  
 c) How many subsets having two elements does  $S$  have?

**Solution:**

$$\text{a) } 2^5 = 32.$$

$$\text{b) } {}^5C_4 = 5.$$

$$\text{c) } {}^5C_2 = 10.$$

22. a) Show that a set having  $n$  elements has  $2^n$  subsets.  
 b) If  $0 < m < n$ , how many subsets are there that have exactly  $m$  elements?

**Solution:**

- a) The number of subsets is

$$\sum_{k=0}^n {}^nC_k = 2^n \quad (1.2.22.1)$$

using the binomial theorem.

- b) The number of subsets having exactly  $m$  elements are  ${}^nC_m$ .

### 1.3 Mappings

1. For the given sets  $S, T$  determine if a mapping  $f : S \rightarrow T$  is clearly and unambiguously defined; if not, say why not.  
 a)  $S$  = set of all women,  $T$  = set of all men,  $f(s)$  = husband of  $s$ .  
 b)  $S$  = set of all positive integers,  $T = S$ ,  $f(s) = s - 1$ .  
 c)  $S$  = set of positive integers,  $T$  = set of nonnegative integers,  $f(s) = s - 1$ .  
 d)  $S$  = set of nonnegative integers,  $T = S$ ,  $f(s) = s - 1$ .

- e)  $S$  = set of all integers,  $T = S$ ,  $f(s) = s - 1$ .  
 f)  $S$  = set of all real numbers,  $T = S$ ,  $f(s) = \sqrt{s}$ .  
 g)  $S$  = set of all positive real numbers,  $T = S$ ,  $f(s) = \sqrt{s}$ .

**Solution:**

- a) Not all women have husbands. So the mapping is not clearly defined.  
 b) For every integer  $s$ ,  $s - 1$  is an integer. So the mapping is defined.  
 c)  $0 \notin S$ , so the mapping is defined.  
 d)  $f(0) = -1 \notin S$ . So the mapping is not defined.  
 e)  $f(-1) \notin S$ , so the mapping is not defined.  
 f)  $f(s) \in S \forall s$ . So the mapping is defined.
2. In those parts of Problem 1.3.1 where  $f$  does define a function, determine if it is 1-1, onto, or both. **Solution:**
- a) For  $f(s) = s - 1$ ,  $s \in \mathbb{Z}$ , the mapping is a bijection.  
 b) For  $s \in \mathbb{N}$ ,  $f(s) = s - 1 \in \mathbb{W}$ , the mapping is a bijection.  
 c) For  $s \in S$ ,  $f(s) \in S$  and vice-versa. So the mapping is a bijection.
3. If  $f$  is a 1-1 mapping of  $S$  onto  $T$ , prove that  $f^{-1}$  is a 1-1 mapping of  $T$  onto  $S$ .

**Solution:** By definition,

$$\begin{aligned} s_1 = s_2 \in S &\implies f(s_1) = f(s_2) \in T \\ t_1 = t_2 \in T &\implies \exists s_1 = s_2 \in S \ni f(s_1) = f(s_2). \end{aligned} \quad (1.3.3.1)$$

Let  $g = f^{-1}$ . Then,

$$f(s_i) = t_i \implies g(t_i) = s_i. \quad (1.3.3.2)$$

From (1.3.3.1),

$$\begin{aligned} g(t_1) = g(t_2) \in S &\implies t_1 = t_2 \in T \\ t_1 = t_2 \in T &\implies \exists g(t_1) = g(t_2) \in S \end{aligned} \quad (1.3.3.3)$$

(1.3.3.3) shows that  $g = f^{-1}$  is also 1-1.

4. If  $f$  is a 1-1 mapping of  $S$  onto  $T$ , prove that  $f^{-1} \circ f = i_S$ .

**Solution:** For  $s \in S$ ,  $t \in T$ ,

$$f(s) = t \implies g(t) = s \quad (1.3.4.1)$$

$$\text{or, } g \circ f(s) = s \implies (g \circ f) = i_S \quad \square \quad (1.3.4.2)$$

5. If  $g : S \rightarrow T$  and  $f : T \rightarrow U$  are both onto, then  $f \circ g : S \rightarrow U$  is also onto.

**Solution:** From the given information,

$$g(S) = T, f(T) = U \quad (1.3.5.1)$$

$$\implies (f \circ g)(S) = U \quad \square \quad (1.3.5.2)$$

6. If  $f : S \rightarrow T$  is onto and  $g : T \rightarrow U$  and  $h : T \rightarrow U$  are such that  $g \circ f = h \circ f$ , prove that  $g = h$ .

**Solution:** From the given information,

$$g \circ f = h \circ f \quad (1.3.6.1)$$

$$\implies (g - h) \circ f = 0 \quad (1.3.6.2)$$

$$\text{or, } g = h \quad (1.3.6.3)$$

7. If  $g : S \rightarrow T$ ,  $h : S \rightarrow T$ , and if  $f : T \rightarrow U$  is 1-1, show that if  $f \circ g = f \circ h$ , then  $g = h$ .  
 8. Let  $S$  be the set of all integers and  $T = \{1, -1\}$ ;  $f : S \rightarrow T$  is defined by

$$f(s) = \begin{cases} 1 & s \text{ even} \\ -1 & s \text{ odd} \end{cases}. \quad (1.3.8.1)$$

- a) Does this define a function from  $S$  to  $T$ ?  
 b) Show that

$$f(s_1 + s_2) = f(s_1)f(s_2) \quad (1.3.8.2)$$

What does this say about the integers?

- c) Is  $f(s_1 s_2) = f(s_1)f(s_2)$  also true?

**Solution:**

- a) Yes,  $f$  is a function.  
 b) See Table 1.3.8.

$f(s_1)$	$f(s_2)$	$f(s_1) + f(s_2)$
1	1	1
1	-1	-1
-1	-1	1
-1	1	-1

TABLE 1.3.8

- c) No. If  $s_1, s_2$  are odd,

$$s_1 s_2 \text{ odd} \quad (1.3.8.3)$$

$$f(s_1 s_2) = -1 \neq f(s_1)f(s_2) \quad (1.3.8.4)$$

9. Let  $S$  be the set of all real numbers. Define

$$f : S \rightarrow S | f(s) = s^2, \quad (1.3.9.1)$$

$$g : S \rightarrow S | g(s) = s + 1, \quad (1.3.9.2)$$

- a) Find  $f \circ g$ .

- b) Find  $g \circ f$ .  
 c) Is  $f \circ g = g \circ f$ ?

**Solution:**

a)

$$(f \circ g)(s) = (s + 1)^2 \quad (1.3.9.3)$$

b)

$$(g \circ f)(s) = s^2 + 1 \quad (1.3.9.4)$$

c) From (1.3.9.3) and (1.3.9.4)  $f \circ g \neq g \circ f$ .

10. Let  $S$  be the set of all real numbers and for  $a, b \in S$ , where  $a \neq 0$ ; define  $f_{a,b}(s) = as + b$ .

a) Show that  $f_{a,b} \circ f_{c,d} = f_{u,v}$  for some real  $u, v$ .  
 Give explicit values for  $u, v$  in terms of  $a, b, c$  and  $d$ .

b) Is  $f_{a,b} \circ f_{c,d} = f_{c,d} \circ f_{a,b}$  always?

c) Find all  $f_{a,b}$  such that  $f_{a,b} \circ f_{1,1} = f_{1,1} \circ f_{a,b}$ .

d) Show that  $f^{-1}$  exists and find its form.

**Solution:**

a)

$$f_{a,b} \circ f_{c,d} = c(as + b) + d \quad (1.3.10.1)$$

$$= cas + cb + d \quad (1.3.10.2)$$

$$= us + v \quad (1.3.10.3)$$

$$\implies u = ca, v = bc + d \quad (1.3.10.4)$$

b) From (1.3.10.1),

$$f_{c,d} \circ f_{a,b} = cas + ad + b \quad (1.3.10.5)$$

Thus, from (1.3.10.1) and (1.3.10.5)

$$f_{a,b} \circ f_{c,d} = f_{c,d} \circ f_{a,b} \quad (1.3.10.6)$$

$$\implies bc + d = ad + b \quad (1.3.10.7)$$

c) From (1.3.10.7),

$$f_{a,b} \circ f_{1,1} = f_{1,1} \circ f_{a,b} \quad (1.3.10.8)$$

$$\implies as + b + 1 = as + a + b \quad (1.3.10.9)$$

$$\text{or, } a = 1. \quad (1.3.10.10)$$

Thus,

$$f_{a,b} = s + b \quad (1.3.10.11)$$

d) From the definition,

$$f_{a,b}(s) = as + b \quad (1.3.10.12)$$

$$\implies s = \frac{f_{a,b}(s) - b}{a} \quad (1.3.10.13)$$

$$\text{or, } f_{a,b}^{-1}(s) = \frac{s - b}{a} \quad (1.3.10.14)$$

11. Let  $S$  be the set of all positive integers. Define  $f : S \rightarrow S$  by  $f(1) = 2, f(2) = 3, f(3) = 1$  and  $f(s) = s$  for any other  $s \in S$ . Show that  $f \circ f \circ f = i_S$ . What is  $f^{-1}$  in this case?

**Solution:** For  $s \in \{1, 2, 3\}$ , it is obvious. For  $s \notin \{1, 2, 3\}$ ,

$$(f \circ f)(s) = f(s) = s \quad (1.3.11.1)$$

$$\implies (f \circ f \circ f)(s) = s \quad \square \quad (1.3.11.2)$$

It is easy to verify that

$$f^{-1}(s) = f(s) = ss \notin \{1, 2, 3\} \quad (1.3.11.3)$$

Also,

$$f^{-1}(2) = f(1), f^{-1}(3) = f(2), f^{-1}(1) = f(3), \quad (1.3.11.4)$$

1.4  $A(S)$  (The set of 1-1 mappings of  $S$  onto itself)

1. If  $s_1 \neq s_2$  are in  $S$ , show that there is an  $f \in A(S)$  such that  $f(s_1) = s_2$ .

**Solution:** By definition of a 1-1 mapping, it is obvious.

2. If  $s_1 \in S$ , let  $H = \{f \in A(S) \mid f(s_1) = s_1\}$ . Show that:

a)  $i \in H$ .

b) If  $f, g \in H$ , then  $fg \in H$ .

c) If  $f \in H$ , then  $f^{-1} \in H$ .

**Solution:**

a)  $\because i(s_1) = s_1, i \in H$ .

b)  $fg(s_1) = f(s_1) = s_1$ .

c)  $f(s_1) = s_1 \implies f^{-1}(s_1) = s_1 \implies f^{-1} \in H$ .

3. Suppose that  $s_1 \neq s_2$  are in  $S$  and  $f(s_1) = s_2$ , where  $f \in A(S)$ . Then if  $H$  is as in Problem 1.4.2 and  $K = \{g \in A(S) \mid g(s_2) = s_2\}$ , show that:

a) If  $g \in K$ , then  $f^{-1}gf \in H$ .

b) If  $h \in H$ , then there is some  $g \in K$  such that  $h = f^{-1}gf$ .

**Solution:**

a) From the given information,

$$f^{-1}gf(s_1) = f^{-1}g(s_2) = f^{-1}(s_2) = s_1 \quad (1.4.3.1)$$

Hence,

$$f^{-1}gf \in H \quad (1.4.3.2)$$

b) The  $h$  was found in the previous part.

4. If  $f, g, h \in A(S)$ , show that  $(f^{-1}gf)(f^{-1}hf) = f^{-1}(gh)f$ . What can you say about  $(f^{-1}gf)^n$ ?

**Solution:** From the given information,

$$(f^{-1}gf)(f^{-1}hf) = f^{-1}g(ff^{-1})hf \quad (1.4.4.1)$$

$$= f^{-1}(gh)f \quad (1.4.4.2)$$

Similarly,

$$(f^{-1}gf)^n = f^{-1}g^n f \quad (1.4.4.3)$$

5. If  $f, g \in A(S)$  and  $fg = gf$ , show that:

a)  $(fg)^2 = f^2g^2$ .

b)  $(fg)^{-1} = f^{-1}g^{-1}$ .

**Solution:** From the given information,

a)

$$(fg)^2 = (fg)(fg) \quad (1.4.5.1)$$

$$= (fg)(gf) = fg^2f \quad (1.4.5.2)$$

$$= f(fg^2) = f^2g^2 \quad (1.4.5.3)$$

b) Since

$$(fg)^{-1}fg = i, \quad (1.4.5.4)$$

$$(fg)^{-1}fgg^{-1} = g^{-1} \quad (1.4.5.5)$$

$$\implies (fg)^{-1}f = g^{-1} \quad (1.4.5.6)$$

$$\implies (fg)^{-1}ff^{-1} = g^{-1}f^{-1} \quad (1.4.5.7)$$

$$\text{or, } (fg)^{-1} = g^{-1}f^{-1} \quad (1.4.5.8)$$

6. Push the result of Problem 1.4.5, for the same  $f$  and  $g$ , to show that

$$(fg)^m = f^m g^m \quad (1.4.6.1)$$

for all integers  $m$ .

**Solution:** Using induction,

$$(fg)^{m+1} = (fg)^m (fg) \quad (1.4.6.2)$$

$$= f^m g^m fg = f^m g^m gf \quad (1.4.6.3)$$

$$= f f^m g^m g \quad (1.4.6.4)$$

yielding (1.4.6.1).

7.

8. If  $f, g \in A(S)$  and  $(fg)^2 = f^2g^2$ , prove that  $fg = gf$ .

**Solution:**

$$(fg)^2 = f^2g^2 \quad (1.4.8.1)$$

$$\implies fgfg = ffgg \quad (1.4.8.2)$$

$$\implies f^{-1}fgfg = f^{-1}ffgg \quad (1.4.8.3)$$

$$\implies gfg = fgg \quad (1.4.8.4)$$

$$\implies gfgg^{-1} = fggg^{-1} \quad (1.4.8.5)$$

yielding the desired result.

## 1.5 The Integers

1. Find  $(a, b)$  and express  $(a, b)$  as  $ma + nb$  for

a)  $(116, -84)$

b)  $(85, 65)$

c)  $(72, 26)$

d)  $(72, 25)$

**Solution:**

a) Using the extended Euclid algorithm,

$$\begin{pmatrix} 116 & 1 & 0 \\ -84 & 0 & 1 \end{pmatrix} \quad (1.5.1.1)$$

$$\xleftrightarrow{R_3 \leftarrow R_1 + R_2} \begin{pmatrix} 32 & 1 & 1 \\ -84 & 0 & 1 \end{pmatrix} \quad (1.5.1.2)$$

$$\xleftrightarrow{R_4 \leftarrow R_2 + 2R_3} \begin{pmatrix} -20 & 2 & 3 \\ -84 & 0 & 1 \end{pmatrix} \quad (1.5.1.3)$$

$$\xleftrightarrow{R_5 \leftarrow R_4 + R_3} \begin{pmatrix} 12 & 3 & 4 \\ -84 & 0 & 1 \end{pmatrix} \quad (1.5.1.4)$$

$$\xleftrightarrow{R_6 \leftarrow R_5 + R_4} \begin{pmatrix} -8 & 5 & 7 \\ -84 & 0 & 1 \end{pmatrix} \quad (1.5.1.5)$$

$$\xleftrightarrow{R_7 \leftarrow R_6 + R_5} \begin{pmatrix} 4 & 8 & 11 \\ -84 & 0 & 1 \end{pmatrix} \quad (1.5.1.6)$$

$$\xleftrightarrow{R_8 \leftarrow R_7 + 2R_6} \begin{pmatrix} 0 & 21 & 29 \\ -84 & 0 & 1 \end{pmatrix} \quad (1.5.1.7)$$

Thus,

$$4 = (8)116 + 11(-84) \quad (1.5.1.8)$$

b)

$$\begin{pmatrix} 85 & 1 & 0 \\ 65 & 0 & 1 \end{pmatrix} \quad (1.5.1.9)$$

$$\xleftrightarrow{R_3 \leftarrow R_1 - R_2} \begin{pmatrix} 20 & 1 & -1 \\ 65 & 0 & 1 \end{pmatrix} \quad (1.5.1.10)$$

$$\xleftrightarrow{R_4 \leftarrow R_2 - 3R_3} \begin{pmatrix} 5 & -3 & 4 \\ 65 & 0 & 1 \end{pmatrix} \quad (1.5.1.11)$$

$$\xleftrightarrow{R_5 \leftarrow R_3 - 4R_4} \begin{pmatrix} 0 & 13 & -17 \\ 65 & 0 & 1 \end{pmatrix} \quad (1.5.1.12)$$

Thus,

$$5 = (-3)85 + 4(65) \quad (1.5.1.13)$$

c)

$$\begin{pmatrix} 72 & 1 & 0 \\ 26 & 0 & 1 \end{pmatrix} \quad (1.5.1.14)$$

$$\xleftrightarrow{R_3 \leftarrow R_1 - 2R_2} \begin{pmatrix} 20 & 1 & -2 \\ 26 & 0 & 1 \end{pmatrix} \quad (1.5.1.15)$$

$$\xleftrightarrow{R_4 \leftarrow R_2 - R_3} \begin{pmatrix} 6 & -1 & 3 \\ 26 & 0 & 1 \end{pmatrix} \quad (1.5.1.16)$$

$$\xleftrightarrow{R_5 \leftarrow R_3 - 3R_4} \begin{pmatrix} 2 & 4 & -11 \\ 26 & 0 & 1 \end{pmatrix} \quad (1.5.1.17)$$

$$\xleftrightarrow{R_6 \leftarrow R_4 - 3R_5} \begin{pmatrix} 0 & -13 & 36 \\ 26 & 0 & 1 \end{pmatrix} \quad (1.5.1.18)$$

Thus,

$$2 = (4)72 + (-11)26 \quad (1.5.1.19)$$

d)

$$\begin{pmatrix} 72 & 1 & 0 \\ 25 & 0 & 1 \end{pmatrix} \quad (1.5.1.20)$$

$$\xleftrightarrow{R_3 \leftarrow R_1 - 2R_2} \begin{pmatrix} 22 & 1 & -2 \\ 25 & 0 & 1 \end{pmatrix} \quad (1.5.1.21)$$

$$\xleftrightarrow{R_4 \leftarrow R_2 - R_3} \begin{pmatrix} 3 & -1 & 3 \\ 25 & 0 & 1 \end{pmatrix} \quad (1.5.1.22)$$

$$\xleftrightarrow{R_5 \leftarrow R_3 - 7R_4} \begin{pmatrix} 1 & 8 & -23 \\ 25 & 0 & 1 \end{pmatrix} \quad (1.5.1.23)$$

Thus,

$$1 = (8)72 + (-23)25 \quad (1.5.1.24)$$

2. Show that the following are true

- $1 \mid n$  for all  $n$ .
- If  $m \neq 0$ , then  $m \mid 0$ .
- If  $m \mid n$  and  $n \mid q$ , then  $m \mid q$ .
- If  $m \mid n$  and  $n \mid q$ , then  $m \mid (un + vq)$  for all  $v, u$ .
- If  $m \mid 1$ , then  $m = 1$  or  $m = -1$ .
- If  $m \mid n$ , and  $n \mid m$ , then  $m = \pm n$ .

**Solution:**

- $n = 1 \times n$ .
- $0 = 0 \times m$ .
- Let

$$n = cm, q = dn. \quad (1.5.2.1)$$

Then

$$q = (cdn)m \implies m \mid q \quad (1.5.2.2)$$

d) Let

$$n = cm, q = dn. \quad (1.5.2.3)$$

Then

$$un + vq = ucm + vdn \quad (1.5.2.4)$$

$$= (uc + vdc)m \quad (1.5.2.5)$$

$$\implies m \mid (un + vq) \quad (1.5.2.6)$$

e) If

$$1 = cm, \quad (1.5.2.7)$$

$$c = 1, m = 1 \quad (1.5.2.8)$$

$$c = -1, m = -1 \quad (1.5.2.9)$$

f)

$$n = cm, m = dn \quad (1.5.2.10)$$

$$\implies mn = cdmn \quad (1.5.2.11)$$

$$\text{or, } cd = 1 \quad (1.5.2.12)$$

Thus, either

$$c = d = 1, \implies n = m, \quad (1.5.2.13)$$

$$\text{or, } c = d = -1, \implies n = -m \quad (1.5.2.14)$$

3. Show that

$$(ma, mb) = m(a, b) \quad m > 0. \quad (1.5.3.1)$$

**Solution:** Let

$$(a, b) = xa + yb \quad (1.5.3.2)$$

Then,

$$(ma, mb) = xma + ymb = m(xa + yb) \quad (1.5.3.3)$$

$$= m(a, b) \quad (1.5.3.4)$$

4. Show that if  $a \mid m$  and  $b \mid m$ , and  $(a, b) = 1$ , then  $(ab) \mid m$ .**Solution:** From the given information,

$$m = ac, \quad (1.5.4.1)$$

$$m = bd,$$

$$ax + by = 1 \quad (1.5.4.2)$$

Multiplying both sides of (1.5.4.2) by  $m$ 

$$max + mby = m \quad (1.5.4.3)$$

$$\implies ab(dx + cy) = m \quad (1.5.4.4)$$

upon substituting from (1.5.4.1). Hence,  $(ab) \mid m$ .

5. Factor the following into primes

a) 36

b) 120



- c) 720  
d) 5040

**Solution:**

- a)  $36 = 2^2 \times 3^2$ .  
b)  $120 = 2^3 \times 3 \times 5$ .  
c)  $720 = 2^4 \times 3^2 \times 5$ .  
d)  $5040 = 2^2 \times 3^2 \times 5 \times 7$ .

6. If  $m = p_1^{a_1} \dots p_k^{a_k}$ , and  $n = p_1^{b_1} \dots p_k^{b_k}$ , where  $p_i$  are distinct primes and  $a_i, b_i$  are nonnegative, express  $(m, n)$  as  $p_1^{c_1} \dots p_k^{c_k}$  by describing the  $c_i$  in terms of the  $a_i$  and  $b_i$ .

**Solution:** Let

$$m = 36 = 2^2 \times 3^2 \quad (1.5.6.1)$$

$$n = 720 = 2^4 \times 3^2 \times 5 \quad (1.5.6.2)$$

Then,

$$k = 3 \quad (1.5.6.3)$$

$$p_1 = 2, p_2 = 3, p_3 = 5 \quad (1.5.6.4)$$

$$a_1 = 2, a_2 = 2, a_3 = 0 \quad (1.5.6.5)$$

$$b_1 = 4, b_2 = 2, b_3 = 1 \quad (1.5.6.6)$$

and

$$(36, 720) = 2^2 \times 3^2 \quad (1.5.6.7)$$

$$\implies c_i = \min(a_i, b_i) \quad (1.5.6.8)$$

7. Define the least common multiple (LCM) of positive integers  $m$  and  $n$  to be the smallest positive integer  $v$  such that both  $m \mid v$  and  $n \mid v$ .

a) Show that

$$v = \frac{mn}{(m, n)} \quad (1.5.7.1)$$

b) In terms of the factorization of  $m$  and  $n$  given in problem 1.5.6 what is  $v$ ?

8. Find the least common multiples of the following pairs

- a) (116, -84)  
b) (85, 65)  
c) (72, 26)  
d) (72, 25)

**Solution:**

- a) 2436.  
b) 1105.  
c) 936.  
d) 1800.

9. If  $m, n > 0$  are two integers, show that we can find integers  $u, v$  with  $-\frac{n}{2} \leq v \leq \frac{n}{2}$  such that  $m = un + v$ .

10. To check that a given integer  $n > 1$  is a prime, prove that it is enough to show that  $n$  is not divisible by any prime  $p$  with  $p \leq \sqrt{n}$ .

## 1.6 Mathematical Induction

1. Prove that

$$1^2 + 2^2 + 3^2 + \dots + n^2 = \frac{n(n+1)(2n+1)}{6} \quad (1.6.1.1)$$

by induction.

**Solution:**  $P(n+1)$  is

$$\begin{aligned} &1^2 + 2^2 + 3^2 + \dots + n^2 + (n+1)^2 \\ &= \frac{n(n+1)(2n+1)}{6} + (n+1)^2 \\ &= (n+1) \left( \frac{2n^2 + 7n + 7}{6} \right) \\ &= \frac{(n+1)(n+2)(2n+3)}{6} \quad (1.6.1.2) \end{aligned}$$

which is true. Hence, the given proposition is true for all  $n \geq 1$

2. Prove that

$$1^3 + 2^3 + 3^3 + \dots + n^3 = \left[ \frac{n(n+1)}{2} \right]^2 \quad (1.6.2.1)$$

by induction.

**Solution:**  $P(n+1)$  is

$$\begin{aligned} &1^3 + 2^3 + 3^3 + \dots + n^3 + (n+1)^3 \\ &= \left[ \frac{n(n+1)}{2} \right]^2 + (n+1)^3 \\ &= (n+1)^2 \left( \frac{n^2 + 4n + 4}{4} \right) \\ &= \left[ \frac{(n+1)(n+2)}{2} \right]^2 \quad (1.6.2.2) \end{aligned}$$

which is true. Hence, the given proposition is true for all  $n \geq 1$ .

3. Prove that a set having  $n \geq 2$  elements has  $\frac{n(n-1)}{2}$  subsets having exactly 2 elements.  
4. Prove that a set having  $n \geq 3$  elements has  $\frac{n(n-1)(n-2)}{3}$  subsets having exactly 3 elements.  
5. If  $n \geq 4$  and  $S$  is a set having  $n$  elements, guess how many subsets having exactly 4 elements are there in  $S$ . Then verify your guess using mathematical induction.

6. If  $p$  is a prime and  $p \mid (a_1 a_2 a_3 \dots a_n)$ , then prove using induction that  $p \mid a_i$  for some  $i$  with  $1 \leq i \leq n$ .
7. If  $a \neq 1$ , prove that

$$1 + a + a^2 + \cdots + a^n = \frac{(a^{n+1} - 1)}{a - 1} \quad (1.6.7.1)$$

by induction.

**Solution:**  $P(n+1)$  can be expressed as

$$\begin{aligned} 1 + a + a^2 + \cdots + a^n + a^{n+1} \\ &= \frac{(a^{n+1} - 1)}{a - 1} + a^{n+1} \\ &= \frac{(a^{n+2} - 1)}{a - 1} \quad (1.6.7.2) \end{aligned}$$

upon simplification. Hence, the given proposition is true for all  $n \geq 1$ .

8. By induction, show that

$$\frac{1}{1 \cdot 2} + \frac{1}{2 \cdot 3} + \cdots + \frac{1}{n \cdot (n+1)} = \frac{n}{n+1} \quad (1.6.8.1)$$

**Solution:**  $P(n + 1)$  can be expressed as

$$\begin{aligned} \frac{1}{1 \cdot 2} + \frac{1}{2 \cdot 3} + \cdots + \frac{1}{n \cdot (n+1)} + \frac{1}{(n+1) \cdot (n+2)} \\ = \frac{n}{n+1} + \frac{1}{(n+1) \cdot (n+2)} \\ = \frac{1}{n+1} \left[ n + \frac{1}{n+2} \right] \\ = \frac{n+1}{n+2} \quad (1.6.8.2) \end{aligned}$$

upon simplification. Hence, the given proposition is true for all  $n \geq 1$ .

9. Suppose that  $P(n)$  is a proposition about positive integers  $n$  such that  $P(n_0)$  is valid, and if  $P(k)$  is true, so must be  $P(k+1)$ . What can you say about  $P(n)$ ? Prove your statement.
10. Let  $P(n)$  be a proposition about integers  $n$  such that  $P(1)$  is true and such that if  $P(j)$  is true for all positive integers  $j < k$ , then  $P(k)$  is true. Prove that  $P(n)$  is true for all positive integers  $n$ .
11. Given an example of a proposition that is *not* true for any positive integer, yet for which the induction step holds.

12. Prove by induction that a set having  $n$  elements has exactly  $2^n$  subsets.

**Solution:** Let  $S = \{1, 2\}$ . Then the subsets are

$$\{\phi\}, \{1\}, \{2\}, \{1, 2\} \quad (1.6.12.1)$$

For  $S = \{1, 2, 3\}$ , the subsets are

$$\{\phi\}, \{1\}, \{2\}, \{1, 2\} \quad (1.6.12.2)$$

$$\{3\}, \{1, 3\}, \{2, 3\}, \{1, 2, 3\} \quad (1.6.12.3)$$

Thus  $P(n+1)$  can be expressed as

$$2^n + 2^n = 2^{n+1} \quad (1.6.12.4)$$

Hence, the given proposition is true for all  $n \geq 1$ .

13. Prove by induction on  $n$  that  $n^3 - n$  is always divisible by 3.

**Solution:**  $P(n + 1)$  can be expressed as

$$\begin{aligned}(n+1)^3 - (n+1) &= n^3 + 3n^2 + 3n + 1 - n - 1 \\ &= n^3 - n + 3(n^2 + n)\end{aligned}\tag{1.6.13.1}\tag{1.6.13.2}$$

which is divisible by 3. Hence, the given proposition is true for all  $n \geq 1$ .

14. If  $p$  is a prime number, then prove that  $n^p - n$  is always divisible by  $p$ .

**Solution:**  $P(n + 1)$  can be expressed as

$$(n+1)^p - (n+1) = n^p - n + p \sum_{k=1}^{n-1} {}^nC_k p^{k-1} \quad (1.6.14.1)$$

$$\implies p \mid [(n+1)^p - (n+1)] \quad (1.6.14.2)$$

Hence, the given proposition is true for all  $n \geq 1$

15. Prove by induction that for a set having  $n$  elements the number of 1-1 mappings of this set onto itself is  $n!$ .

**Solution:** Let  $S = \{a, b, c\}$ . Then the possible 1-1 onto mappings are

$$\begin{array}{cccccc} \left\{ \begin{array}{l} a \mapsto b \\ b \mapsto c \\ c \mapsto a \end{array} \right. & \left\{ \begin{array}{l} a \mapsto b \\ b \mapsto a \\ c \mapsto c \end{array} \right. & \left\{ \begin{array}{l} a \mapsto c \\ b \mapsto b \\ c \mapsto a \end{array} \right. & \left\{ \begin{array}{l} a \mapsto a \\ b \mapsto c \\ c \mapsto b \end{array} \right. & \left\{ \begin{array}{l} a \mapsto a \\ b \mapsto b \\ c \mapsto c \end{array} \right. & \left\{ \begin{array}{l} a \mapsto a \\ b \mapsto c \\ c \mapsto a \end{array} \right. \\ (1.6.15.1) \end{array}$$

## 1.7 Complex Numbers

### 1. Multiply

- a)  $(6 - 7j)(8 + j)$   
 b)  $\left(\frac{2}{3} + \frac{3}{2}j\right)\left(\frac{2}{3} - \frac{3}{2}j\right)$   
 c)  $(6 + 7j)(8 - j)$

**Solution:**

a)

$$(6 - 7j)(8 + j) = \begin{pmatrix} 6 & 7 \\ -7 & 6 \end{pmatrix} \begin{pmatrix} 8 \\ 1 \end{pmatrix} \quad (1.7.1.1)$$

$$= \begin{pmatrix} 53 \\ -50 \end{pmatrix} = 53 - 50j \quad (1.7.1.2)$$

b)

$$\left(\frac{2}{3} + \frac{3}{2}j\right)\left(\frac{2}{3} - \frac{3}{2}j\right) = \begin{pmatrix} \frac{2}{3} & -\frac{3}{2} \\ \frac{3}{2} & \frac{2}{3} \end{pmatrix} \begin{pmatrix} \frac{2}{3} \\ -\frac{3}{2} \end{pmatrix} \quad (1.7.1.3)$$

$$= \begin{pmatrix} \frac{97}{36} \\ 0 \end{pmatrix} = \frac{97}{36} \quad (1.7.1.4)$$

c)

$$\begin{aligned} (6 + 7j)8 - j &= [(6 - 7j)8 + j]^* \quad (1.7.1.5) \\ &= (53 - 50j)^* = 53 + 50j \quad (1.7.1.6) \end{aligned}$$

### 2. Find $z^{-1}$ for

- a)  $z = 6 + 8j$   
 b)  $z = 6 - 8j$   
 c)  $z = \frac{1}{\sqrt{2}}(1 + j)$

**Solution:**

a)

$$z^{-1} = \frac{z^*}{|z|^2} = \frac{6 - 8j}{100} \quad (1.7.2.1)$$

b)

$$z^{-1} = \frac{6 + 8j}{100} \quad (1.7.2.2)$$

c)

$$z^{-1} = \frac{1 - j}{\sqrt{2}} \quad (1.7.2.3)$$

### 3. Show that

$$(z^*)^{-1} = (z^{-1})^* \quad (1.7.3.1)$$

**Solution:** Since

$$zz^{-1} = 1, \quad (1.7.3.2)$$

$$(zz^{-1})^* = 1 \quad (1.7.3.3)$$

$$\Rightarrow (z)^*(z^{-1})^* = 1 \quad (1.7.3.4)$$

yielding (1.7.3.1).

### 4. Find

$$(\cos \theta + j \sin \theta)^{-1} \quad (1.7.4.1)$$

**Solution:**

$$(\cos \theta + j \sin \theta)^{-1} = \cos \theta - j \sin \theta \quad (1.7.4.2)$$

### 5. Verify the following

a)  $(z^*)^* = z$

b)  $(z + w)^* = z^* + w^*$

c)  $z + z^* = 2\text{Re}(z)$

d)  $z - z^* = 2j\text{Im}(z)$

**Solution:**

a) For

$$z = a + jb, \quad (1.7.5.1)$$

$$z^* = a - jb, \quad (1.7.5.2)$$

$$\Rightarrow (z^*)^* = a + jb = z \quad (1.7.5.3)$$

b) For

$$z = z_1 + jz_2 \quad (1.7.5.4)$$

$$w = w_1 + jw_2,$$

$$(z + w)^* = (z_1 + jz_2 + w_1 + jw_2)^* \quad (1.7.5.5)$$

$$= (z_1 - jz_2) + (w_1 - jw_2) \quad (1.7.5.6)$$

$$= z^* + w^* \quad (1.7.5.7)$$

c) For

$$z = a + jb, \quad (1.7.5.8)$$

$$z^* = a - jb, \quad (1.7.5.9)$$

$$\Rightarrow (z + z^*) = a + jb + a - jb \quad (1.7.5.10)$$

$$= 2a = 2\text{Re}(z) \quad (1.7.5.11)$$

d) For

$$z = a + jb, \quad (1.7.5.12)$$

$$z^* = a - jb, \quad (1.7.5.13)$$

$$\Rightarrow (z - z^*) = a + jb - a - jb \quad (1.7.5.14)$$

$$= 2jb = 2j\text{Im}(z) \quad (1.7.5.15)$$

6. Show that  $z$  is real if and only if  $z^* = z$  and is purely imaginary if and only if  $z^* = -z$ .

**Solution:** Let

$$z = a + jb. \quad (1.7.6.1)$$

Then

$$z^* = a - jb. \quad (1.7.6.2)$$

If

$$z^* = z, \quad (1.7.6.3)$$

$$a + jb = a - jb \quad (1.7.6.4)$$

$$\implies b = 0 \quad (1.7.6.5)$$

and  $z$  is real. If  $z$  is real,

$$z = a \quad (1.7.6.6)$$

$$\implies z^* = a \quad (1.7.6.7)$$

$$\text{or, } z = z^* \quad (1.7.6.8)$$

Similarly, the other property can be proved.

7. Verify the commutative law of multiplication  $zw = wz$  in  $\mathbb{C}$ .

**Solution:** Let

$$z = a + jb \quad (1.7.7.1)$$

$$w = x - jy \quad (1.7.7.2)$$

Then

$$zw = \begin{pmatrix} a & -b \\ b & a \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} \quad (1.7.7.3)$$

$$= \begin{pmatrix} x & -y \\ y & x \end{pmatrix} \begin{pmatrix} a \\ b \end{pmatrix} \quad (1.7.7.4)$$

$$= wz \quad (1.7.7.5)$$

8. Show that for  $z \neq 0$ ,  $|z|^{-1} = \frac{1}{|z|}$ .

**Solution:** Let

$$z = re^{j\theta}. \quad (1.7.8.1)$$

Then

$$z^{-1} = \frac{1}{r} e^{-j\theta} \quad (1.7.8.2)$$

$$\implies |z^{-1}| = \frac{1}{r} \quad (1.7.8.3)$$

9. Find

a)  $|6 - 4j|$ .

b)  $\left| \frac{1}{2} + \frac{2}{3}j \right|$ .

c)  $\left| \frac{1}{\sqrt{2}} (1 + j) \right|$

**Solution:**

a)

$$|6 - 4j| = \sqrt{6^2 + 4^2} = 2\sqrt{13} \quad (1.7.9.1)$$

b)

$$\left| \frac{1}{2} + \frac{2}{3}j \right| = \frac{5}{6} \quad (1.7.9.2)$$

c)

$$\left| \frac{1}{\sqrt{2}} (1 + j) \right| = \frac{1}{\sqrt{2}} |(1 + j)| = 1 \quad (1.7.9.3)$$

10. Show that  $|z^*| = |z|$ .

**Solution:** Let

$$z = re^{j\theta} \quad (1.7.10.1)$$

Then

$$z^* = re^{-j\theta} \quad (1.7.10.2)$$

$$\implies |z^*| = r = |z|. \quad (1.7.10.3)$$

11. Find the polar form for

a)  $z = \frac{\sqrt{2}}{2} - \frac{1}{\sqrt{2}}j$ .

b)  $z = 4j$ .

c)  $z = \frac{6}{\sqrt{2}} + \frac{6}{\sqrt{2}}j$ .

d)  $z = -\frac{13}{2} + \frac{39}{2\sqrt{3}}j$ .

**Solution:**

a)

$$|z| = \sqrt{\left(\frac{\sqrt{2}}{2}\right)^2 + \left(\frac{1}{\sqrt{2}}\right)^2}. \quad (1.7.11.1)$$

$$= 1 \quad (1.7.11.2)$$

and

$$\angle z = -\tan^{-1} \frac{\frac{1}{\sqrt{2}}}{\frac{\sqrt{2}}{2}} \quad (1.7.11.3)$$

$$= \frac{\pi}{4} \quad (1.7.11.4)$$

b)

$$|z| = 4, \angle z = \frac{\pi}{2}. \quad (1.7.11.5)$$

c)

$$|z| = \frac{6}{\sqrt{2}}, \angle z = \frac{\pi}{4}. \quad (1.7.11.6)$$

d)

$$|z| = \frac{13}{2} \sqrt{1+3} \quad (1.7.11.7)$$

$$= 13 \quad (1.7.11.8)$$

and

$$\angle z = \pi - \tan^{-1} \frac{\frac{39}{2\sqrt{3}}}{\frac{13}{2}} \quad (1.7.11.9)$$

$$= \pi - \tan^{-1} \sqrt{3} = \frac{2\pi}{3} \quad (1.7.11.10)$$

12. Prove that

$$\left( \cos\left(\frac{\theta}{2}\right) + j \sin\left(\frac{\theta}{2}\right) \right)^2 = \cos(\theta) + j \sin(\theta) \quad (1.7.12.1)$$

**Solution:** The L.H.S can be expressed as

$$(e^{j\theta})^2 = e^{j2\theta} \quad (1.7.12.2)$$

13. Show that

$$\left( \frac{1}{2} + \frac{\sqrt{3}}{2}j \right)^3 = -1 \quad (1.7.13.1)$$

**Solution:**

$$\frac{1}{2} + \frac{\sqrt{3}}{2}j = e^{j\frac{\pi}{3}} \quad (1.7.13.2)$$

$$\Rightarrow \left( e^{j\frac{\pi}{3}} \right)^3 = e^{j\pi} = -1 \quad (1.7.13.3)$$

14. Show that

$$(\cos(\theta) + j \sin(\theta))^m = \cos(m\theta) + j \sin(m\theta) \quad (1.7.14.1)$$

for all integers  $m$ . **Solution:** It is easy to verify that

$$(\cos(\theta) + j \sin(\theta))^2 = \cos(2\theta) + j \sin(2\theta) \quad (1.7.14.2)$$

Then

$$\begin{aligned} (\cos(\theta) + j \sin(\theta))^{k+1} &= (\cos(\theta) + j \sin(\theta))^k \\ &\quad (\cos(\theta) + j \sin(\theta)) \\ &= \cos[(k+1)\theta] + j \sin((k+1)\theta) \end{aligned} \quad (1.7.14.3)$$

By induction, (1.7.14.1) is proved.

15. Show that

$$(\cos(\theta) + j \sin(\theta))^r = \cos(r\theta) + j \sin(r\theta) \quad (1.7.15.1)$$

for all rational numbers  $r$ . **Solution:** Let

$$r = \frac{m}{n}, (\cos(\theta) + j \sin(\theta))^{\frac{1}{n}} = \cos(\alpha) + j \sin(\alpha) \quad (1.7.15.2)$$

Then

$$(\cos(\alpha) + j \sin(\alpha))^n = (\cos(\theta) + j \sin(\theta)) \quad (1.7.15.3)$$

$$\Rightarrow \cos(n\alpha) + j \sin(n\alpha) = (\cos(\theta) + j \sin(\theta)) \quad (1.7.15.4)$$

$$\text{or, } \alpha = \frac{\theta}{n} \quad (1.7.15.5)$$

yielding

$$(\cos(\theta) + j \sin(\theta))^{\frac{1}{n}} = \cos\left(\frac{\theta}{n}\right) + j \sin\left(\frac{\theta}{n}\right) \quad (1.7.15.6)$$

Using (1.7.14.1) and (1.7.15.6),

$$(\cos(\theta) + j \sin(\theta))^{\frac{m}{n}} = \cos\left(\frac{m\theta}{n}\right) + j \sin\left(\frac{m\theta}{n}\right) \quad (1.7.15.7)$$

16. If  $z \in \mathbb{C}$  and  $n \geq 1$  is any positive integer, show that there are  $n$  distinct complex numbers such that  $z = w^n$ . **Solution:** Let

$$z = \cos(\theta) + j \sin(\theta) \quad (1.7.16.1)$$

then using (1.7.15.6),

$$w = \cos\left(\frac{2\pi k + \theta}{n}\right) + j \sin\left(\frac{2\pi k + \theta}{n}\right), k = 0, \dots, n-1 \quad (1.7.16.2)$$

which are the distinct roots.

17. Find the necessary and sufficient condition on  $k$  such that

$$\left( \cos\left(\frac{2\pi k}{n}\right) + j \sin\left(\frac{2\pi k}{n}\right) \right)^n = 1 \quad \text{and} \quad (1.7.17.1)$$

$$\left( \cos\left(\frac{2\pi k}{n}\right) + j \sin\left(\frac{2\pi k}{n}\right) \right)^m \neq 1 \quad 0 < m < n \quad (1.7.17.2)$$

**Solution:** From the above equations, using (1.7.14.1),

$$\frac{mk}{n} \notin \mathbb{Z} \quad (1.7.17.3)$$

18. Viewing the  $x$ - $y$  plane as the set of all complex numbers  $x + jy$ , show that multiplication by  $j$  induces as  $90^\circ$  rotation of the  $x$ - $y$  plan in counterclockwise direction.

**Solution:** The given multiplication can be expressed using matrices as

$$\begin{pmatrix} \cos 90^\circ & -\sin 90^\circ \\ \sin 90^\circ & \cos 90^\circ \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} \quad (1.7.18.1)$$

which is the multiplication of  $\begin{pmatrix} x \\ y \end{pmatrix}$  with a  $90^\circ$  rotation matrix.

19. In problem (1.7.18), interpret geometrically what multiplication by the complex number  $a + jb$  does to the  $x - y$  plane.

**Solution:** The multiplication can be represented as

$$\sqrt{a^2 + b^2} \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} \quad (1.7.19.1)$$

where

$$\cos \theta = \frac{a}{\sqrt{a^2 + b^2}} \sin \theta = \frac{b}{\sqrt{a^2 + b^2}} \quad (1.7.19.2)$$

Geometrically, multiplication by  $a + jb$  results in rotation by  $\theta$  and scaling by  $\sqrt{a^2 + b^2}$ .

20. Prove that

$$|z + w|^2 + |z - w|^2 = 2(|z|^2 + |w|^2) \quad (1.7.20.1)$$

**Solution:** Since

$$|z + w|^2 = (z + w)^* (z + w) \quad (1.7.20.2)$$

$$= |z|^2 + |w|^2 + 2z^*w \quad (1.7.20.3)$$

and

$$|z - w|^2 = (z - w)^* (z - w) \quad (1.7.20.4)$$

$$= |z|^2 + |w|^2 - 2z^*w, \quad (1.7.20.5)$$

$$|z + w|^2 + |z - w|^2 = 2(|z|^2 + |w|^2) \quad (1.7.20.6)$$

21. Consider the set  $A = a + bJ, a, b \in \mathbb{Z}$ . Prove that there is 1-1 correspondence of  $A$  onto  $\mathbb{N}$ .

22. If  $a$  is a (complex) root of the polynomial

$$x^n + \alpha_1 x^{n-1} + \cdots + \alpha_{n-1} x + \alpha_n, \quad (1.7.22.1)$$

where the  $\alpha_i$  are real, show that  $\bar{a}$  must also be a root.

**Solution:** From the given information,

$$\bar{a}^n + \alpha_1 \bar{a}^{n-1} + \cdots + \alpha_{n-1} \bar{a} + \alpha_n = 0 \quad (1.7.22.2)$$

Thus,  $\bar{a}$  is also a root of the given polynomial.

23. Find the necessary and sufficient conditions on  $z$  and  $w$  in order that

$$|z + w| = |z| + |w| \quad (1.7.23.1)$$

**Solution:**

$$|z + w|^2 = |z|^2 + |w|^2 + 2z^*w \quad (1.7.23.2)$$

$$(|z| + |w|)^2 = |z|^2 + |w|^2 + 2|z||w| \quad (1.7.23.3)$$

If the above expressions are equal,

$$z^*w = |z||w| \quad (1.7.23.4)$$

which is the desired condition.

24. Find the necessary and sufficient conditions on  $z_i$  in order that

$$\left| \sum_{i=1}^k z_i \right| = \sum_{i=1}^k |z_i| \quad (1.7.24.1)$$

**Solution:**

$$\left| \sum_{i=1}^k z_i \right|^2 = \sum_{i=1}^k |z_i|^2 + 2 \sum_{\substack{i=1, j=1 \\ i \neq j}}^k z_i^* z_j \quad (1.7.24.2)$$

$$\left( \sum_{i=1}^k |z_i| \right)^2 = \sum_{i=1}^k |z_i|^2 + 2 \sum_{\substack{i=1, j=1 \\ i \neq j}}^k |z_i| |z_j| \quad (1.7.24.3)$$

From (1.7.24.2) and (1.7.24.3),

$$\begin{aligned} \sum_{i=1}^k |z_i|^2 + 2 \sum_{\substack{i=1, j=1 \\ i \neq j}}^k z_i^* z_j \\ = \sum_{i=1}^k |z_i|^2 + 2 \sum_{\substack{i=1, j=1 \\ i \neq j}}^k |z_i| |z_j| \\ \Rightarrow \sum_{\substack{i=1, j=1 \\ i \neq j}}^k z_i^* z_j \\ = \sum_{\substack{i=1, j=1 \\ i \neq j}}^k |z_i| |z_j| \end{aligned} \quad (1.7.24.4)$$

which is the desired condition.

25. The complex number  $\theta$  is said to have *order*  $n \geq 1$  if  $\theta^n = 1$  and  $\theta^m \neq 1$  for  $0 < m < n$ . Show that if  $\theta$  has order  $n$  and  $\theta^k = 1$ , where  $k > 0$ , then  $n|k$ .

**Solution:** From the given information,

$$\theta^n = \theta^k = 1, k \geq n \quad (1.7.25.1)$$

If  $n \nmid k, k = mn + p, 0 < p < n$ , Then,

$$\theta^k = \theta^{mn+p} = \theta^p \neq 1, \quad (1.7.25.2)$$

which is a contradiction, Hence,  $n | k$ .

26. Find all complex numbers  $\theta$  having order  $n$ .

**Solution:** If

$$\theta^n = 1, \quad (1.7.26.1)$$

$$\theta^n = e^{j2\pi r}, 0 \leq r < n \quad (1.7.26.2)$$

yielding

$$\theta = \exp\left(j\frac{2\pi r}{n}\right) 0 \leq r < n \quad (1.7.26.3)$$

## 2 GROUPS

### 2.1 Definitions and Examples of Groups

1. Determine if the following sets  $G$  with the operation indicated form a group. If not, point out which of the group axioms fail.

- $G$  = set of all integers,  $a * b = a - b$ .
- $G$  = set of all integers,  $a * b = a + b + ab$
- $G$  = set of nonnegative integers,  $a * b = a + b$ .
- $G$  = set of all rational numbers  $\neq -1$ ,  $a * b = a + b + ab$ .
- $G$  = set of all rational numbers with denominator divisible by 5 (written so that numerator and denominator are relatively prime),  $a * b = a + b$ .
- $G$  a set having more than one element,  $a * b = a \forall a, b \in G$ .

**Solution:** The properties of a group are

- $a, b \in G \implies a * b \in G$ .
  - $a, b, c \in G \implies a * (b * c) = (a * b) * c \in G$ .
  - $\exists e \in G \ni a * i = i * a = a \forall a \in G$ .
  - $a \in G \implies \exists b \in G \ni a * b = b * a = i$ .
- a) From 2.1.1b,

$$a * (b * c) = a - (b - c) = a - b + c \quad (2.1.1.1)$$

$$(a * b) * c = (a - b) - c = a - b - c \quad (2.1.1.2)$$

$$\implies a * (b * c) \neq (a * b) * c \quad (2.1.1.3)$$

Thus,  $G$  is not a group.

b) i) From property 2.1.1b,

$$a * (b * c) = a * (b + c + bc) \quad (2.1.1.4)$$

$$= a + b + c + bc + a(b + c + bc) \quad (2.1.1.5)$$

$$= a + b + c + ab + bc + ca + abc \quad (2.1.1.6)$$

$$(a * b) * c = (a + b + ab) + c + c(a + b + ab) \quad (2.1.1.7)$$

$$= a + b + c + ab + bc + ca + abc \quad (2.1.1.8)$$

Thus, property 2.1.1b is satisfied.

ii) Since

$$a * i = a + i + ai \quad (2.1.1.9)$$

$$i * a = a + i + ai \quad (2.1.1.10)$$

property 2.1.1c is satisfied.

iii)

$$a * i = a + i + ai \quad (2.1.1.11)$$

$$i * a = a + i + ai \quad (2.1.1.12)$$

Thus, for property 2.1.1c to be satisfied,

$$i * a = a \quad (2.1.1.13)$$

$$\implies a + i + ai = a \quad (2.1.1.14)$$

$$\text{or, } i(1 + a) = 0 \quad (2.1.1.15)$$

$$\implies i = 0 \quad (2.1.1.16)$$

iv) If

$$a * b = b * a = i, \quad (2.1.1.17)$$

$$a + b + ab = 0 \quad (2.1.1.18)$$

$$\implies b = -\frac{a}{1 + a} \quad (2.1.1.19)$$

which is not finite for  $a = -1$ . Also,  $b \notin G$  for  $a = 1$ . Thus, property 2.1.1d is violated and  $G$  is not a group.

c) In this case, for property 2.1.1c to be satisfied,

$$a * i = i * a = a, \quad (2.1.1.20)$$

$$\implies a + i = a \quad (2.1.1.21)$$

$$\text{or, } i = 0 \quad (2.1.1.22)$$

From property 2.1.1c,

$$a + b = 0 \implies b = -a \quad (2.1.1.23)$$

Thus,  $G$  is a group.

d) From problem 2.1.1b, it is easy to verify that  $G$  is a group, since we are now considering rational numbers.

e) From property 2.1.1c,

$$a * i = a, i * a = i \quad (2.1.1.24)$$

$$\implies a = i \quad (2.1.1.25)$$

From property 2.1.1d,

$$a * b = b * a = i \quad (2.1.1.26)$$

$$\implies i * b = i, b * i = b = i \quad (2.1.1.27)$$

Thus,  $G$  has only a single element  $i$  which is a contradiction. So  $G$  is not a group.

2. Let  $G$  be the set of all mappings

$$T_{a,b} \mid T_{a,b}(r) = ar + b, \quad a \neq 0, b, r \in \mathbb{R}, \quad (2.1.2.1)$$

show that the set  $H = T_{a,b} \mid a = \pm 1, b \in \mathbb{R}$  forms a group under the  $*$  of  $G$ .

**Solution:**

a)

$$(T_{a,b} * T_{a,c})(r) = a(ar + c) + b \quad (2.1.2.2)$$

$$= a^2r + ac + b = r + ac + b \quad (2.1.2.3)$$

$$= T_{1,ac+b} \in G \quad (2.1.2.4)$$

Similarly,

$$(T_{a,c} * T_{a,b})(r) = r + ab + c \quad (2.1.2.5)$$

b) If

$$(T_{a,b} * T_{a,c})(r) = T_{a,b}, \quad (2.1.2.6)$$

$$r + ab + c = ar + b \quad (2.1.2.7)$$

$$\implies a = 1, c = 0 \quad (2.1.2.8)$$

Thus,

$$i = T_{1,0} \quad (2.1.2.9)$$

c) If

$$(T_{a,b} * T_{a,c})(r) = (T_{a,c} * T_{a,b})(r) = T_{1,0}, \quad (2.1.2.10)$$

$$r + ab + c = r + ac + b = r \quad (2.1.2.11)$$

$$\implies b = \pm c \quad (2.1.2.12)$$

d) From (2.1.2.4),

$$T_{a,b} * (T_{a,c}(r) * T_{a,d})(r) = T_{a,b} * T_{1,ad+c} \quad (2.1.2.13)$$

$$= a(r + ad + b + c) + b \quad (2.1.2.14)$$

$$= ar + ab + ac + b + d \quad (2.1.2.15)$$

Similarly,

$$(T_{a,b} * T_{a,c})(r) * T_{a,d}(r) = T_{1,ac+b} * T_{a,d} \quad (2.1.2.16)$$

$$= (ar + d) + ac + b \quad (2.1.2.17)$$

$$= ar + ab + ac + b + d \quad (2.1.2.18)$$

which satisfies the associativity property.

Thus,  $T_{a,b}^{-1} = T_{a,\pm b}$ . and  $G$  is a group.

3. Let  $H \subset G$ , for  $G$  in problem 2.1.2d and  $H = \{T_{a,b} \in G \mid a \text{ is rational, } b \text{ any real}\}$ . Show that  $H$  is also a group.

4. Let  $K \subset G$ , for  $G$  in problem 2.1.2d and  $K = \{T_{1,b} \in G \mid b \in \mathbb{R}\}$ . Show that  $K$  is an Abelian group.

**Solution:** From (2.1.2.4),

$$T_{1,b} * T_{1,c} = T_{1,b+c} \quad (2.1.4.1)$$

$$= T_{1,c+b} \quad (2.1.4.2)$$

Thus,  $K$  is an Abelian group.

5. Let  $S = \{(x, y) \mid x, y \in \mathbb{R}\}$  and consider  $f, g \in A(S)$  defined by  $f(x, y) = (-x, y)$  and  $g(x, y) = (-y, x)$ ;  $f$  is the reflection about the  $y$ -axis and  $g$  is the rotation through  $90^\circ$  in a counterclockwise direction about the origin. We then define  $G = \{f^i g^j \mid i = 0, 1; j = 0, 1, 2, 3\}$ , and let  $*$  in  $G$  be the product of elements in  $A(S)$ . Clearly,  $f^2 = g^4 = \text{identity mapping}$ ;  $(f * g)(x, y) = (fg)(x, y) = f(g(x, y)) = f(-y, x) = (y, x)$  and  $(g * f)(x, y) = g(f(x, y)) = g(-x, y) = (-y, -x)$ . Prove that  $g * f = f * g^{-1}$ , and that  $G$  is a group, is nonabelian, and is of order 8.

**Solution:** Let

$$\mathbf{x} = \begin{pmatrix} x \\ y \end{pmatrix}. \quad (2.1.5.1)$$

Then

$$f(\mathbf{x}) = \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} \mathbf{x} = \mathbf{fx} \quad (2.1.5.2)$$

$$g(\mathbf{x}) = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \mathbf{x} = \mathbf{gx} \quad (2.1.5.3)$$

and

$$\mathbf{gf} = \begin{pmatrix} 0 & -1 \\ -1 & 0 \end{pmatrix} = \mathbf{fg}^{-1} \quad (2.1.5.4)$$

Let

$$\mathbf{G}_1 = \mathbf{f}^i \mathbf{g}^j \in G \quad (2.1.5.5)$$

$$\mathbf{G}_2 = \mathbf{f}^k \mathbf{g}^l \in G \quad (2.1.5.6)$$

a) The identity element is

$$\mathbf{i} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \quad (2.1.5.7)$$



b) It is easy to verify that

$$\mathbf{f}^{-1} = \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} \quad (2.1.5.8)$$

$$\mathbf{g}^{-1} = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \quad (2.1.5.9)$$

Also,

$$\mathbf{f}^i \mathbf{g}^j \mathbf{g}^{-j} \mathbf{f}^{-i} = \mathbf{i} \quad (2.1.5.10)$$

and

$$\mathbf{g}^{-j} \mathbf{f}^{-i} \mathbf{f}^i \mathbf{g}^j = \mathbf{i} \quad (2.1.5.11)$$

which implies that all elements in  $G$  have an inverse.

c) The product

$$\mathbf{G}_1 \mathbf{G}_2 = \mathbf{f}^i \mathbf{g}^j \mathbf{f}^k \mathbf{g}^l \in G \quad (2.1.5.12)$$

For  $j > k$ ,

$$\mathbf{f}^i \mathbf{g}^{j-k} \mathbf{g}^k \mathbf{f}^k \mathbf{g}^l = \mathbf{f}^i \mathbf{g}^{j-k} \mathbf{f}^k \mathbf{g}^{l-k} \quad (2.1.5.13)$$

if  $l > k$ .

6.

7.

8. If  $G$  is an Abelian group, prove that  $(a * b)^n = a^n * b^n$  for all integers  $n$ .

**Solution:** For  $n = 1$ , the above result is valid.

For  $n = 2$ ,

$$(a * b)^2 = a * b * a * b = a * a * b * b = a^2 * b^2 \quad (2.1.8.1)$$

Let  $P(n)$  be true. Then,  $P(n + 1)$  can be expressed as

$$(a * b)^{n+1} = (a * b)^n * a * b \quad (2.1.8.2)$$

$$= a^n * b^n * a * b = a^n * a * b^n * b \quad (2.1.8.3)$$

$$= a^{n+1} b^{n+1} \quad (2.1.8.4)$$

9. If  $G$  is a group in which  $a^2 = e$  for all  $a \in G$ , show that  $G$  is abelian.

**Solution:**

$$\because e \in G, e^2 = e \quad (2.1.9.1)$$

$$\implies \quad (2.1.9.2)$$