



MATHEMATICS

Textbook for Class XII

PART I



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PART I



राष्ट्रीय शैक्षिक अनुसंधान और प्रशिक्षण परिषद्
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Foreword

The National Curriculum Framework, 2005, recommends that children's life at school must be linked to their life outside the school. This principle marks a departure from the legacy of bookish learning which continues to shape our system and causes a gap between the school, home and community. The syllabi and textbooks developed on the basis of NCF signify an attempt to implement this basic idea. They also attempt to discourage rote learning and the maintenance of sharp boundaries between different subject areas. We hope these measures will take us significantly further in the direction of a child-centred system of education outlined in the National Policy on Education (1986).

The success of this effort depends on the steps that school principals and teachers will take to encourage children to reflect on their own learning and to pursue imaginative activities and questions. We must recognise that, given space, time and freedom, children generate new knowledge by engaging with the information passed on to them by adults. Treating the prescribed textbook as the sole basis of examination is one of the key reasons why other resources and sites of learning are ignored. Inculcating creativity and initiative is possible if we perceive and treat children as participants in learning, not as receivers of a fixed body of knowledge.

These aims imply considerable change in school routines and mode of functioning. Flexibility in the daily time-table is as necessary as rigour in implementing the annual calendar so that the required number of teaching days are actually devoted to teaching. The methods used for teaching and evaluation will also determine how effective this textbook proves for making children's life at school a happy experience, rather than a source of stress or boredom. Syllabus designers have tried to address the problem of curricular burden by restructuring and reorienting knowledge at different stages with greater consideration for child psychology and the time available for teaching. The textbook attempts to enhance this endeavour by giving higher priority and space to opportunities for contemplation and wondering, discussion in small groups, and activities requiring hands-on experience.

NCET appreciates the hard work done by the textbook development committee responsible for this book. We wish to thank the Chairperson of the advisory group in Science and Mathematics, Professor .. Narlikar and the Chief advisor for this book, Professor P. ain for guiding the work of this committee. Several teachers contributed to the development of this textbook we are grateful to their principals for making this possible. We are indebted to the institutions and organisations which have generously permitted us to draw upon their resources, material and personnel. s an organisation committed to systemic reform and continuous improvement in the quality of its products, NCET welcomes comments and suggestions which will enable us to undertake further revision and refinement.

New Delhi
20 December 2005

Director
National Council of Educational
Research and Training

Preface

The National Council of Educational research and Training (NCET) had constituted 21 Focus groups on Teaching of various subjects related to School Education, to review the National Curriculum Framework for School Education - 2000 (NCFSE - 2000) in face of new emerging challenges and transformations occurring in the fields of content and pedagogy under the contexts of National and International spectrum of school education. These Focus groups made general and specific comments in their respective areas. Consequently, based on these reports of Focus groups, National Curriculum Framework (NCF)-2005 was developed.

NCET designed the new syllabi and constituted Textbook development Teams for Classes I and II to prepare textbooks in mathematics under the new guidelines and new syllabi. The textbook for Class I is already in use, which was brought in 2005.

The first draft of the present book (Class II) was prepared by the team consisting of NCET faculty, experts and practicing teachers. The draft was refined by the development team in different meetings. This draft of the book was exposed to a group of practicing teachers teaching mathematics at higher secondary stage in different parts of the country, in a review workshop organised by the NCET at Delhi. The teachers made useful comments and suggestions which were incorporated in the draft textbook. The draft textbook was finalised by an editorial board constituted out of the development team. Finally, the advisory group in Science and Mathematics and the Monitoring Committee constituted by the Ministry, Government of India have approved the draft of the textbook.

In the fitness of things, let us cite some of the essential features dominating the textbook. These characteristics have reflections in almost all the chapters. The existing textbook contain 1 main chapters and two appendices. Each Chapter contain the followings

- Introduction highlighting the importance of the topic connection with earlier studied topics brief mention about the new concepts to be discussed in the chapter.
- Organisation of chapter into sections comprising one or more conceptsub concepts.
- Motivating and introducing the conceptsub concepts. Illustrations have been provided wherever possible.

- Proofsproblem solving involving deductive or inductive reasoning, multiplicity of approaches wherever possible have been inducted.
- eometric viewing visualisation of concepts have been emphasised whenever needed.
- pplications of mathematical concepts have also been integrated with allied subjects like science and social sciences.
- dequate and variety of examplesexercises have been given in each section.
- For refocusing and strengthening the understanding and skill of problem solving and applicabilities, miscellaneous types of examplesexercises have been provided involving two or more sub concepts at a time at the end of the chapter. The scope of challenging problems to talented minority have been reflected conducive to the recommendation as reflected in NCF-2005.
- For more motivational purpose, brief historical background of topics have been provided at the end of the chapter and at the beginning of each chapter relevant quotation and photograph of eminent mathematician who have contributed significantly in the development of the topic undertaken, are also provided.
- astly, for direct recapitulation of main concepts, formulas and results, brief summary of the chapter has also been provided.

I am thankful to Professor rishan umar, irector, NCET who constituted the team and invited me to join this national endeavor for the improvement of mathematics education. e has provided us with an enlightened perspective and a very conducive environment. This made the task of preparing the book much more enjoyable and rewarding. I express my gratitude to Professor .. Narlikar, Chairperson of the dvisory roup in Science and Mathematics, for his specific suggestions and advice towards the improvement of the book from time to time. I, also, thank Prof. . avindra, oint irector, NCET for his help from time to time.

I express my sincere thanks to Professor ukum Singh, Chief Coordinator and ead ESM, r. . P. Singh, Coordinator and Professor S. . Singh autam who have been helping for the success of this project academically as well as administratively. Iso, I would like to place on records my appreciation and thanks to all the members of the team and the teachers who have been associated with this noble cause in one or the other form.

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**THE CONSTITUTION OF
INDIA
PREAMBLE**

WE, THE PEOPLE OF INDIA, having solemnly resolved to constitute India into a ¹**[SOVEREIGN SOCIALIST SECULAR DEMOCRATIC REPUBLIC]** and to secure to all its citizens :

JUSTICE, social, economic and political;

LIBERTY of thought, expression, belief, faith and worship;

EQUALITY of status and of opportunity; and to promote among them all

FRATERNITY assuring the dignity of the individual and the ²[unity and integrity of the Nation];

IN OUR CONSTITUENT ASSEMBLY this twenty-sixth day of November, 1949 do **HEREBY ADOPT, ENACT AND GIVE TO OURSELVES THIS CONSTITUTION.**

1. Subs. by the Constitution (Forty-second Amendment) Act, 1976, Sec.2, for "Sovereign Democratic Republic" (w.e.f. 3.1.1977)
2. Subs. by the Constitution (Forty-second Amendment) Act, 1976, Sec.2, for "Unity of the Nation" (w.e.f. 3.1.1977)

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Constitution of India

Part IV A (Article 51 A)

Fundamental Duties

It shall be the duty of every citizen of India

- (a) to abide by the Constitution and respect its ideals and institutions, the National Flag and the National Anthem
- (b) to cherish and follow the noble ideals which inspired our national struggle for freedom
- (c) to uphold and protect the sovereignty, unity and integrity of India
- (d) to defend the country and render national service when called upon to do so
- (e) to promote harmony and the spirit of common brotherhood amongst all the people of India transcending religious, linguistic and regional or sectional diversities to renounce practices derogatory to the dignity of women
- (f) to value and preserve the rich heritage of our composite culture
- (g) to protect and improve the natural environment including forests, lakes, rivers, wildlife and to have compassion for living creatures
- (h) to develop the scientific temper, humanism and the spirit of inquiry and reform
- (i) to safeguard public property and to abjure violence
- (j) to strive towards excellence in all spheres of individual and collective activity so that the nation constantly rises to higher levels of endeavour and achievement
- (k) who is a parent or guardian, to provide opportunities for education to his child or, as the case may be, ward between the age of six and fourteen years.

Note: The Article 51 containing Fundamental Duties was inserted by the Constitution (42nd Amendment) Act, 1972 (with effect from January 1972).

(k) was inserted by the Constitution (86th Amendment) Act, 2002 (with effect from April 1, 2002).

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Arvinder Chawla

RELATIONS AND FUNCTIONS

❖ *There is no permanent place in the world for ugly mathematics It may be very hard to define mathematical beauty but that is just as true of beauty of any kind, we may not know quite what we mean by a beautiful poem, but that does not prevent us from recognising one when we read it. — G. H. HARDY* ❖

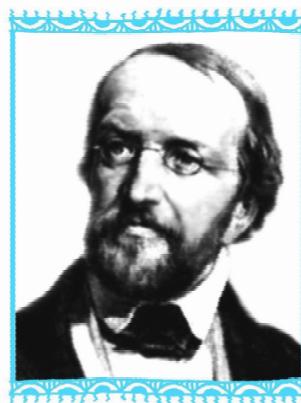
1.1 Introduction

Recall that the notion of relations and functions, domain, co-domain and range have been introduced in Class XI along with different types of specific real valued functions and their graphs. The concept of the term ‘relation’ in mathematics has been drawn from the meaning of relation in English language, according to which two objects or quantities are related if there is a recognisable connection or link between the two objects or quantities. Let A be the set of students of Class XII of a school and B be the set of students of Class XI of the same school. Then some of the examples of relations from A to B are

- (i) $\{(a, b) \in A \times B: a \text{ is brother of } b\}$,
- (ii) $\{(a, b) \in A \times B: a \text{ is sister of } b\}$,
- (iii) $\{(a, b) \in A \times B: \text{age of } a \text{ is greater than age of } b\}$,
- (iv) $\{(a, b) \in A \times B: \text{total marks obtained by } a \text{ in the final examination is less than the total marks obtained by } b \text{ in the final examination}\}$,
- (v) $\{(a, b) \in A \times B: a \text{ lives in the same locality as } b\}$. However, abstracting from this, we define mathematically a relation R from A to B as an arbitrary subset of $A \times B$.

If $(a, b) \in R$, we say that a is related to b under the relation R and we write as $a R b$. In general, $(a, b) \in R$, we do not bother whether there is a recognisable connection or link between a and b . As seen in Class XI, functions are special kind of relations.

In this chapter, we will study different types of relations and functions, composition of functions, invertible functions and binary operations.



Lejeune Dirichlet
(1805-1859)

1.2 Types of Relations

In this section, we would like to study different types of relations. We know that a relation in a set A is a subset of $A \times A$. Thus, the empty set \emptyset and $A \times A$ are two extreme relations. For illustration, consider a relation R in the set $A = \{1, 2, 3\}$ given by $R = \{(a, b) : a < b\}$. This is the empty set, as no pair (a, b) satisfies the condition $a < b$. Similarly, $R' = \{(a, b) : a < b \leq 3\}$ is the whole set $A \times A$, as all pairs (a, b) in $A \times A$ satisfy $a < b \leq 3$. These two extreme examples lead us to the following definitions.

Definition 1 A relation R in a set A is called *empty relation*, if no element of A is related to any element of A , i.e., $R = \emptyset \subseteq A \times A$.

Definition 2 A relation R in a set A is called *universal relation*, if each element of A is related to every element of A , i.e., $R = A \times A$.

Both the empty relation and the universal relation are sometimes called *trivial relations*.

Example 1 Let A be the set of all students of a boys school. Show that the relation R in A given by $R = \{(a, b) : a \text{ is sister of } b\}$ is the empty relation and $R' = \{(a, b) : \text{the difference between heights of } a \text{ and } b \text{ is less than } 2 \text{ meters}\}$ is the universal relation.

Solution Since the school is a boys school, no student of the school can be a sister of any student of the school. Hence, $R = \emptyset$, showing that R is the empty relation. It is also obvious that the difference between heights of any two students of the school has to be less than 2 meters. This shows that $R' = A \times A$ is the universal relation.

Remark In Class XI, we have seen two ways of representing a relation, namely roster method and set builder method. However, a relation R in the set $\{1, 2, 3\}$ defined by $R = \{(a, b) : b < a\}$ is also expressed as $a R b$ if and only if $b < a$ by many authors. We may also use this notation, as and when convenient.

If $(a, b) \in R$, we say that a is related to b and we denote it as $a R b$.

One of the most important relations, which plays a significant role in Mathematics, is an *equivalence relation*. To study an equivalence relation, we first consider three types of relations, namely reflexive, symmetric and transitive.

Definition 3 A relation R in a set A is called

- (i) *reflexive*, if $(a, a) \in R$, for every $a \in A$,
- (ii) *symmetric*, if $(a, b) \in R$ implies that $(b, a) \in R$, for all $a, b \in A$.
- (iii) *transitive*, if $(a, b) \in R$ and $(b, c) \in R$ implies that $(a, c) \in R$, for all $a, b, c \in A$.

In Example 5, note that all even integers are related to zero, as $(0, 2), (0, 4), \dots$ etc., lie in R and no odd integer is related to zero, as $(0, 1), (0, 3), \dots$ etc., do not lie in R . Similarly, all odd integers are related to one and no even integer is related to one. Therefore, the set E of all even integers and the set of all odd integers are subsets of \mathbb{Z} satisfying following conditions:

- (i) All elements of E are related to each other and all elements of O are related to each other.
- (ii) No element of E is related to any element of O and vice-versa.
- (iii) E and O are disjoint and $\mathbb{Z} = E \cup O$.

The subset E is called the *equivalence class containing zero* and is denoted by $[0]$. Similarly, $[1]$ is the equivalence class containing one and is denoted by $[1]$. Note that

$[r] = \{x \in \mathbb{Z} : x \sim r\}$ and $[r] \cap [s] = \emptyset, r \neq s, r, s \in \mathbb{Z}$. In fact, what we have seen above is true for an arbitrary equivalence relation R in a set X . Given an arbitrary equivalence relation R in an arbitrary set X , R divides X into mutually disjoint subsets A_i called partitions or subdivisions of X satisfying:

- (i) all elements of A_i are related to each other, for all i .
- (ii) no element of A_i is related to any element of $A_j, i \neq j$.
- (iii) $\bigcup A_i = X$ and $A_i \cap A_j = \emptyset, i \neq j$.

The subsets A_i are called *equivalence classes*. The interesting part of the situation is that we can go reverse also. For example, consider a subdivision of the set \mathbb{Z} given by three mutually disjoint subsets A_1, A_2 and A_3 whose union is \mathbb{Z} with

$$\begin{aligned} A_1 &= \{x \in \mathbb{Z} : x \text{ is a multiple of } 3\} = \{\dots, -6, -3, 0, 3, 6, \dots\} \\ A_2 &= \{x \in \mathbb{Z} : x \text{ is a multiple of } 2 \text{ but not } 3\} = \{\dots, -4, -2, 2, 4, \dots\} \\ A_3 &= \{x \in \mathbb{Z} : x \text{ is not a multiple of } 2 \text{ or } 3\} = \{\dots, -5, -1, 1, 5, \dots\} \end{aligned}$$

Define a relation R in \mathbb{Z} given by $R = \{(a, b) : 3 \text{ divides } a - b\}$. Following the arguments similar to those used in Example 5, we can show that R is an equivalence relation. Also, A_1 coincides with the set of all integers in \mathbb{Z} which are related to zero, A_2 coincides with the set of all integers which are related to -2 and A_3 coincides with the set of all integers in \mathbb{Z} which are related to -1 . Thus, $A_1 = [0], A_2 = [-2]$ and $A_3 = [-1]$. In fact, $A_i = [r], A_j = [s]$ and $A_k = [t],$ for all $r, s, t \in \mathbb{Z}$.

Example 6 Let R be the relation defined in the set $A = \{1, 2, 3, 4, 5, 6, \dots\}$ by $R = \{(a, b) : \text{both } a \text{ and } b \text{ are either odd or even}\}$. Show that R is an equivalence relation. Further, show that all the elements of the subset $\{1, 3, 5, \dots\}$ are related to each other and all the elements of the subset $\{2, 4, 6, \dots\}$ are related to each other, but no element of the subset $\{1, 3, 5, \dots\}$ is related to any element of the subset $\{2, 4, 6, \dots\}$.

Solution Given any element a in A , both a and a must be either odd or even, so that $(a, a) \in R$. Further, $(a, b) \in R \Rightarrow$ both a and b must be either odd or even $\Rightarrow (b, a) \in R$. Similarly, $(a, b) \in R$ and $(b, c) \in R \Rightarrow$ all elements a, b, c , must be either even or odd simultaneously $\Rightarrow (a, c) \in R$. Hence, R is an equivalence relation. Further, all the elements of $\{1, 3, 5, \dots\}$ are related to each other, as all the elements of this subset are odd. Similarly, all the elements of the subset $\{2, 4, 6, \dots\}$ are related to each other, as all of them are even. Also, no element of the subset $\{1, 3, 5, \dots\}$ can be related to any element of $\{2, 4, 6, \dots\}$, as elements of $\{1, 3, 5, \dots\}$ are odd, while elements of $\{2, 4, 6, \dots\}$ are even.

EXERCISE 1.1

- Determine whether each of the following relations are reflexive, symmetric and transitive:
 - Relation R in the set $A = \{1, 2, 3, \dots, 10\}$ defined as $R = \{(x, y) : x = y\}$
 - Relation R in the set \mathbf{N} of natural numbers defined as $R = \{(x, y) : y = x \text{ and } x \in \mathbf{N}\}$
 - Relation R in the set $A = \{1, 2, 3, 4, 5, 6, 7, 8, 9, 10\}$ as $R = \{(x, y) : y \text{ is divisible by } x\}$
 - Relation R in the set \mathbf{Z} of all integers defined as $R = \{(x, y) : x - y \text{ is an integer}\}$
 - Relation R in the set A of human beings in a town at a particular time given by
 - $R = \{(x, y) : x \text{ and } y \text{ work at the same place}\}$
 - $R = \{(x, y) : x \text{ and } y \text{ live in the same locality}\}$
 - $R = \{(x, y) : x \text{ is exactly } 5 \text{ cm taller than } y\}$
 - $R = \{(x, y) : x \text{ is wife of } y\}$
 - $R = \{(x, y) : x \text{ is father of } y\}$
- Show that the relation R in the set \mathbf{R} of real numbers, defined as $R = \{(a, b) : a \leq b\}$ is neither reflexive nor symmetric nor transitive.
- Check whether the relation R defined in the set $\{1, 2, 3, 4, 5, 6, 7, 8, 9, 10\}$ as $R = \{(a, b) : b = a\}$ is reflexive, symmetric or transitive.
- Show that the relation R in \mathbf{R} defined as $R = \{(a, b) : a \leq b\}$, is reflexive and transitive but not symmetric.
- Check whether the relation R in \mathbf{R} defined by $R = \{(a, b) : a \leq b\}$ is reflexive, symmetric or transitive.

6. how that the relation R in the set $\{, , \}$ given by $R = \{(,), (,)\}$ is symmetric but neither reflexive nor transitive.
7. how that the relation R in the set A of all the books in a library of a college, given by $R = \{(x, y) : x \text{ and } y \text{ have same number of pages}\}$ is an equivalence relation.
8. how that the relation R in the set A $\{, , , \}$ given by $R = \{(a, b) : a - b \text{ is even}\}$, is an equivalence relation. how that all the elements of $\{, , \}$ are related to each other and all the elements of $\{, \}$ are related to each other. But no element of $\{, , \}$ is related to any element of $\{, \}$.
9. how that each of the relation R in the set A $\{x \in \mathbf{Z} : -2 \leq x \leq 2\}$, given by
 - (i) $R = \{(a, b) : a - b \text{ is a multiple of } 2\}$
 - (ii) $R = \{(a, b) : a = b\}$
 is an equivalence relation. find the set of all elements related to in each case.
10. give an example of a relation. which is
 - (i) symmetric but neither reflexive nor transitive.
 - (ii) Transitive but neither reflexive nor symmetric.
 - (iii) Reflexive and symmetric but not transitive.
 - (iv) Reflexive and transitive but not symmetric.
 - (v) symmetric and transitive but not reflexive.
11. how that the relation R in the set A of points in a plane given by $R = \{(P, Q) : \text{distance of the point } P \text{ from the origin is same as the distance of the point } Q \text{ from the origin}\}$, is an equivalence relation. further, show that the set of all points related to a point $P \neq (0, 0)$ is the circle passing through P with origin as centre.
12. how that the relation R defined in the set A of all triangles as $R = \{(T_1, T_2) : T_1 \text{ is similar to } T_2\}$, is equivalence relation. Consider three right angle triangles T_1 with sides a, b, c , T_2 with sides ka, kb, kc and T_3 with sides ka, kb, kc . which triangles among T_1, T_2 and T_3 are related
13. how that the relation R defined in the set A of all polygons as $R = \{(P, Q) : P \text{ and } Q \text{ have same number of sides}\}$, is an equivalence relation. what is the set of all elements in A related to the right angle triangle T with sides a, b, c and
14. Let L be the set of all lines in X plane and R be the relation in L defined as $R = \{(L_1, L_2) : L_1 \text{ is parallel to } L_2\}$. how that R is an equivalence relation. find the set of all lines related to the line $y = x$.

15. Let R be the relation in the set $\{, , , \}$ given by $R = \{(,), (,), (,), (,), (,), (,), (,)\}$. Choose the correct answer.
- (A) R is reflexive and symmetric but not transitive.
 (B) R is reflexive and transitive but not symmetric.
 (C) R is symmetric and transitive but not reflexive.
 (D) R is an equivalence relation.
16. Let R be the relation in the set \mathbb{N} given by $R = \{(a, b) : a \leq b, b \in \mathbb{N}\}$. Choose the correct answer.
- (A) $(,) \in R$ (B) $(,) \in R$ (C) $(,) \in R$ (D) $(,) \in R$

1.3 Types of Functions

The notion of a function along with some special functions like identity function, constant function, polynomial function, rational function, modulus function, signum function etc. along with their graphs have been given in Class XI.

Addition, subtraction, multiplication and division of two functions have also been studied. As the concept of function is of paramount importance in mathematics and among other disciplines as well, we would like to extend our study about function from where we finished earlier. In this section, we would like to study different types of functions.

Consider the functions f, f, f and f given by the following diagrams.

In fig. , we observe that the images of distinct elements of X under the function f are distinct, but the image of two distinct elements and of X under f is same, namely b . Further, there are some elements like e and f in X which are not images of any element of X under f , while all elements of X are images of some elements of X under f . The above observations lead to the following definitions:

Definition 5 A function $f: X \rightarrow Y$ is defined to be *one-one* (or *injective*), if the images of distinct elements of X under f are distinct, i.e., for every $x, x' \in X, f(x) = f(x')$ implies $x = x'$. otherwise, f is called *many-one*.

The function f and f in fig. (i) and (iv) are one-one and the function f and f in fig. (ii) and (iii) are many-one.

Definition 6 A function $f: X \rightarrow Y$ is said to be *onto* (or *surjective*), if every element of Y is the image of some element of X under f , i.e., for every $y \in Y$, there exists an element x in X such that $f(x) = y$.

The function f and f in fig. (iii), (iv) are onto and the function f in fig. (i) is not onto as elements e, f in X are not the image of any element in X under f .

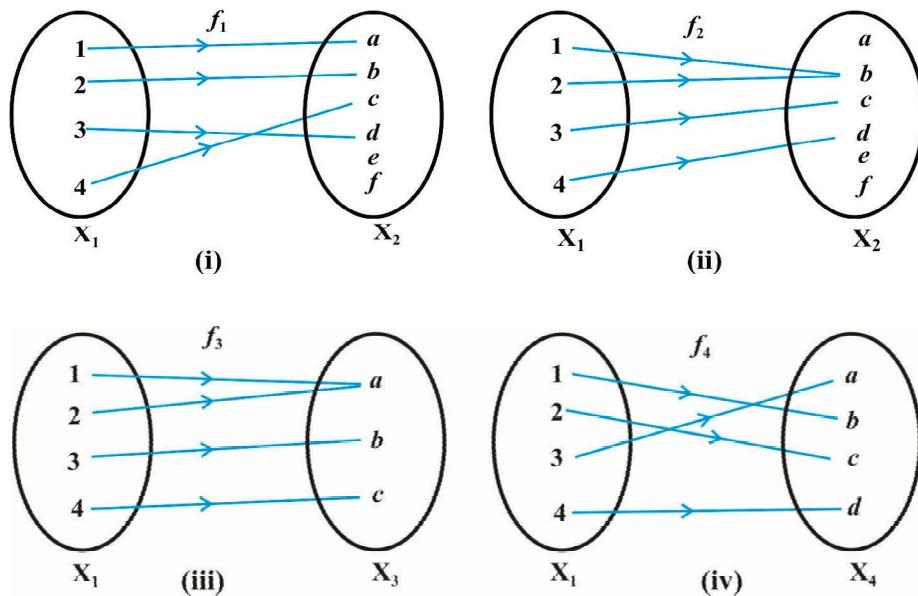


Fig 1.2 (i) to (iv)

Remark $f: X \rightarrow Y$ is onto if and only if Range of $f = Y$.

Definition 7 A function $f: X \rightarrow Y$ is said to be *one-one* and *onto* (or *bijective*), if f is both one-one and onto.

The function f in fig. (iv) is one-one and onto.

Example 7 Let A be the set of all students of Class X in a school. Let $f: A \rightarrow \mathbb{N}$ be function defined by $f(x)$ = roll number of the student x . Show that f is one-one but not onto.

Solution No two different students of the class can have same roll number. Therefore, f must be one-one. We can assume without any loss of generality that roll numbers of students are from 1 to n . This implies that $n+1 \in \mathbb{N}$ is not roll number of any student of the class, so that $n+1$ can not be image of any element of A under f . Hence, f is not onto.

Example 8 Show that the function $f: \mathbb{N} \rightarrow \mathbb{N}$, given by $f(x) = 2x$, is one-one but not onto.

Solution The function f is one-one, for $f(x) = f(y) \Rightarrow 2x = 2y \Rightarrow x = y$. Further, f is not onto, as for $1 \in \mathbb{N}$, there does not exist any x in \mathbb{N} such that $f(x) = 1$.

Example 9 Prove that the function $f: \mathbf{R} \rightarrow \mathbf{R}$, given by $f(x) = 2x$, is one-one and onto.

Solution f is one-one, as $f(x) = f(x) \Rightarrow 2x = 2x \Rightarrow x = x$. Also, given any real number y in \mathbf{R} , there exists $\frac{y}{2}$ in \mathbf{R} such that $f(\frac{y}{2}) = 2(\frac{y}{2}) = y$. Hence, f is onto.

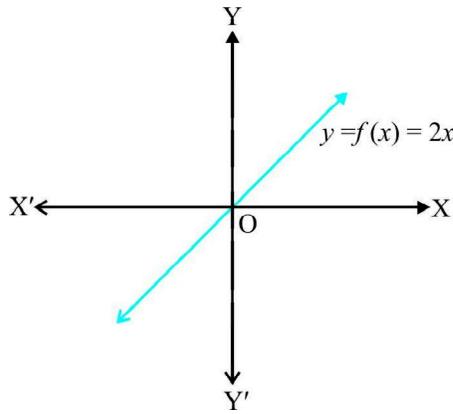


Fig 1.3

Example 10 Show that the function $f: \mathbf{N} \rightarrow \mathbf{N}$, given by $f(0) = 0$ and $f(x) = x + 1$, for every $x \in \mathbf{N}$, is onto but not one-one.

Solution f is not one-one, as $f(0) = 0$ and $f(1) = 1$. But f is onto, as given any $y \in \mathbf{N}$, $y \neq 0$, we can choose x as $y - 1$ such that $f(y - 1) = (y - 1) + 1 = y$. Also for $0 \in \mathbf{N}$, we have $f(0) = 0$.

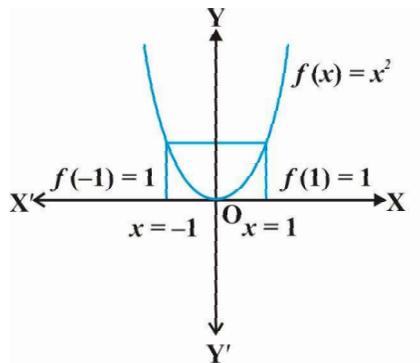
Example 11 Show that the function $f: \mathbf{R} \rightarrow \mathbf{R}$, defined as $f(x) = x^2$, is neither one-one nor onto.

Solution Since $f(-1) = 1$ and $f(1) = 1$, f is not one-one. Also, the element -1 in the co-domain \mathbf{R} is not image of any element x in the domain \mathbf{R} (hy). Therefore f is not onto.

Example 12 Show that $f: \mathbf{N} \rightarrow \mathbf{N}$, given by

$$f(x) = \begin{cases} x + 1, & \text{if } x \text{ is odd,} \\ x - 1, & \text{if } x \text{ is even} \end{cases}$$

is both one-one and onto.



The image of 1 and -1 under f is 1.

Fig 1.4

Solution suppose $f(x) = f(x)$. Note that if x is odd and x is even, then we will have $x = x$, i.e., $x = x$ which is impossible. Similarly, the possibility of x being even and x being odd can also be ruled out, using the similar argument. Therefore, both x and x must be either odd or even. Suppose both x and x are odd. Then $f(x) = f(x) \Rightarrow x = x \Rightarrow x = x$. Similarly, if both x and x are even, then also $f(x) = f(x) \Rightarrow x = x \Rightarrow x = x$. Thus, f is one-one. Also, any odd number r in the co-domain \mathbf{N} is the image of $r + 1$ in the domain \mathbf{N} and any even number r in the co-domain \mathbf{N} is the image of r in the domain \mathbf{N} . Thus, f is onto.

Example 13 Show that an onto function $f: \{1, 2, 3\} \rightarrow \{1, 2, 3\}$ is always one-one.

Solution Suppose f is not one-one. Then there exists two elements, say a and b in the domain whose image in the co-domain is same. Also, the image of a under f can be only one element. Therefore, the range set can have at the most two elements of the co-domain $\{1, 2, 3\}$, showing that f is not onto, a contradiction. Hence, f must be one-one.

Example 14 Show that a one-one function $f: \{1, 2, 3\} \rightarrow \{1, 2, 3\}$ must be onto.

Solution Since f is one-one, three elements of $\{1, 2, 3\}$ must be taken to different elements of the co-domain $\{1, 2, 3\}$ under f . Hence, f has to be onto.

Remark The results mentioned in Examples 13 and 14 are also true for an arbitrary finite set X , i.e., a one-one function $f: X \rightarrow X$ is necessarily onto and an onto map $f: X \rightarrow X$ is necessarily one-one, for every finite set X . In contrast to this, Examples 15 and 16 show that for an infinite set, this may not be true. In fact, this is a characteristic difference between a finite and an infinite set.

EXERCISE 1.2

1. Show that the function $f: \mathbf{R}_* \rightarrow \mathbf{R}_*$ defined by $f(x) = \frac{1}{x}$ is one-one and onto, where \mathbf{R}_* is the set of all non-zero real numbers. Is the result true, if the domain \mathbf{R}_* is replaced by \mathbf{N} with co-domain being same as \mathbf{R}_* ?
2. Check the injectivity and surjectivity of the following functions:
 - (i) $f: \mathbf{N} \rightarrow \mathbf{N}$ given by $f(x) = x$
 - (ii) $f: \mathbf{Z} \rightarrow \mathbf{Z}$ given by $f(x) = x$
 - (iii) $f: \mathbf{R} \rightarrow \mathbf{R}$ given by $f(x) = x$
 - (iv) $f: \mathbf{N} \rightarrow \mathbf{N}$ given by $f(x) = x$
 - (v) $f: \mathbf{Z} \rightarrow \mathbf{Z}$ given by $f(x) = x$
3. Prove that the greatest Integer function $f: \mathbf{R} \rightarrow \mathbf{R}$, given by $f(x) = [x]$, is neither one-one nor onto, where $[x]$ denotes the greatest integer less than or equal to x .

1.4 Composition of Functions and Invertible Function

In this section, we will study composition of functions and the inverse of a bijective function. Consider the set A of all students, who appeared in Class X of a Board Examination in . Each student appearing in the Board Examination is assigned a roll number by the Board which is written by the students in the answer script at the time of examination. In order to have confidentiality, the Board arranges to deface the roll numbers of students in the answer scripts and assigns a fake code number to each roll number. Let $B \subset \mathbb{N}$ be the set of all roll numbers and $C \subset \mathbb{N}$ be the set of all code numbers. This gives rise to two functions $f: A \rightarrow B$ and $g: B \rightarrow C$ given by $f(a)$ the roll number assigned to the student a and $g(b)$ the code number assigned to the roll number b . In this process each student is assigned a roll number through the function f and each roll number is assigned a code number through the function g . Thus, by the combination of these two functions, each student is eventually attached a code number.

This leads to the following definition:

Definition 8 Let $f: A \rightarrow B$ and $g: B \rightarrow C$ be two functions. Then the composition of f and g , denoted by $g \circ f$, is defined as the function $g \circ f: A \rightarrow C$ given by

$$g \circ f(x) = g(f(x)), \forall x \in A.$$

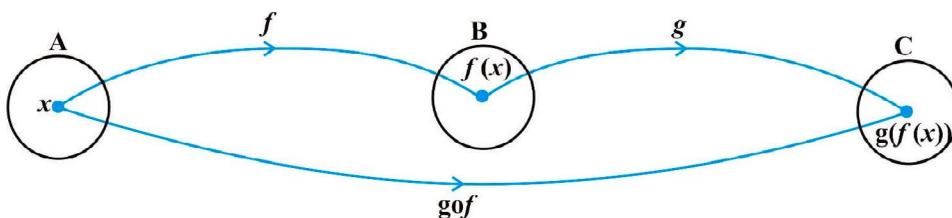


Fig 1.5

Example 15 Let $f: \{1, 2, 3\} \rightarrow \{1, 2, 3\}$ and $g: \{1, 2, 3\} \rightarrow \{1, 2, 3\}$ be functions defined as $f(1) = 2, f(2) = 1, f(3) = 3$ and $g(1) = 1, g(2) = 3, g(3) = 2$. Find $g \circ f$.

Solution We have $g \circ f(1) = g(f(1)) = g(2) = 3, g \circ f(2) = g(f(2)) = g(1) = 1, g \circ f(3) = g(f(3)) = g(3) = 2$. Hence $g \circ f(1) = 3, g \circ f(2) = 1, g \circ f(3) = 2$.

Example 16 Find $g \circ f$ and $f \circ g$, if $f: \mathbb{R} \rightarrow \mathbb{R}$ and $g: \mathbb{R} \rightarrow \mathbb{R}$ are given by $f(x) = \cos x$ and $g(x) = x^2$. Show that $g \circ f \neq f \circ g$.

Solution We have $g \circ f(x) = g(f(x)) = g(\cos x) = (\cos x)^2 = \cos^2 x$. Similarly, $f \circ g(x) = f(g(x)) = f(x^2) = \cos(x^2)$. Note that $\cos^2 x \neq \cos(x^2)$, for $x = \frac{\pi}{2}$. Hence, $g \circ f \neq f \circ g$.

Example 17 how that if $f: \mathbf{R} - \left\{ - \right\} \rightarrow \mathbf{R} - \left\{ - \right\}$ is defined by $f(x) = \frac{x+}{x-}$ and

$g: \mathbf{R} - \left\{ - \right\} \rightarrow \mathbf{R} - \left\{ - \right\}$ is defined by $g(x) = \frac{x+}{x-}$, then $f \circ g \text{ I}_A$ and $g \circ f \text{ I}_B$, where,

$A = \mathbf{R} - \left\{ - \right\}, B = \mathbf{R} - \left\{ - \right\}$ $I_A(x) = x, \forall x \in A, I_B(x) = x, \forall x \in B$ are called identity functions on sets A and B, respectively.

Solution e have

$$g \circ f(x) = g\left(\frac{x+}{x-}\right) = \frac{\left(\frac{x+}{x-}\right)^+}{\left(\frac{x+}{x-}\right)^-} = \frac{\frac{x+}{x-}}{\frac{x+}{x-}} = \frac{x+}{x-} = x$$

imilarly, $f \circ g(x) = f\left(\frac{x+}{x-}\right) = \frac{\left(\frac{x+}{x-}\right)^+}{\left(\frac{x+}{x-}\right)^-} = \frac{\frac{x+}{x-}}{\frac{x+}{x-}} = \frac{x+}{x-} = x$

Thus, $g \circ f(x) = x, \forall x \in B$ and $f \circ g(x) = x, \forall x \in A$, which implies that $g \circ f \text{ I}_B$ and $f \circ g \text{ I}_A$.

Example 18 how that if $f: A \rightarrow B$ and $g: B \rightarrow C$ are one-one, then $g \circ f: A \rightarrow C$ is also one-one.

Solution suppose $g \circ f(x) = g \circ f(x')$

- $\Rightarrow g(f(x)) = g(f(x'))$
- $\Rightarrow f(x) = f(x')$, as g is one-one
- $\Rightarrow x = x'$, as f is one-one

Hence, $g \circ f$ is one-one.

Example 19 how that if $f: A \rightarrow B$ and $g: B \rightarrow C$ are onto, then $g \circ f: A \rightarrow C$ is also onto.

Solution given an arbitrary element $z \in C$, there exists a pre-image y of z under g such that $g(y) = z$, since g is onto. further, for $y \in B$, there exists an element x in A

with $f(x) = y$, since f is onto. Therefore, $gof(x) = g(f(x)) = g(y) = z$, showing that gof is onto.

Example 20 Consider functions f and g such that composite gof is defined and is one-one. Are f and g both necessarily one-one.

Solution Consider $f: \{1, 2, 3\} \rightarrow \{1, 2, 3, 4\}$ defined as $f(x) = x, \forall x$ and $g: \{1, 2, 3, 4\} \rightarrow \{1, 2, 3, 4\}$ as $g(x) = x$, for $x = 1, 2$, and $g(3) = g(4)$. Then, $gof(x) = x \forall x$, which shows that gof is one-one. But g is clearly not one-one.

Example 21 Are f and g both necessarily onto, if gof is onto

Solution Consider $f: \{1, 2, 3\} \rightarrow \{1, 2, 3\}$ and $g: \{1, 2, 3\} \rightarrow \{1, 2\}$ defined as $f(1) = 1, f(2) = 2, f(3) = 1, g(1) = 1, g(2) = 2$ and $g(3) = 1$. It can be seen that gof is onto but f is not onto.

Remark It can be verified in general that gof is one-one implies that f is one-one. Similarly, gof is onto implies that g is onto.

Now, we would like to have close look at the functions f and g described in the beginning of this section in reference to a Board Examination. Each student appearing in Class X Examination of the Board is assigned a roll number under the function f and each roll number is assigned a code number under g . After the answer scripts are examined, examiner enters the mark against each code number in a mark book and submits to the office of the Board. The Board officials decode by assigning roll number back to each code number through a process reverse to g and thus mark gets attached to roll number rather than code number. Further, the process reverse to f assigns a roll number to the student having that roll number. This helps in assigning mark to the student scoring that mark. We observe that while composing f and g , to get gof , first f and then g was applied, while in the reverse process of the composite gof , first the reverse process of g is applied and then the reverse process of f .

Example 22 Let $f: \{1, 2, 3\} \rightarrow \{a, b, c\}$ be one-one and onto function given by $f(1) = a, f(2) = b$ and $f(3) = c$. Show that there exists a function $g: \{a, b, c\} \rightarrow \{1, 2, 3\}$ such that $gof = I_X$ and $fog = I_Y$, where, $X = \{1, 2, 3\}$ and $Y = \{a, b, c\}$.

Solution Consider $g: \{a, b, c\} \rightarrow \{1, 2, 3\}$ as $g(a) = 1, g(b) = 2$ and $g(c) = 3$. It is easy to verify that the composite $gof = I_X$ is the identity function on X and the composite $fog = I_Y$ is the identity function on Y .

Remark The interesting fact is that the result mentioned in the above example is true for an arbitrary one-one and onto function $f: X \rightarrow Y$. Not only this, even the converse is also true, i.e., if $f: X \rightarrow Y$ is a function such that there exists a function $g: Y \rightarrow X$ such that $gof = I_X$ and $fog = I_Y$, then f must be one-one and onto.

The above discussion, Example and Remark lead to the following definition:

Definition 9 A function $f: X \rightarrow Y$ is defined to be *invertible*, if there exists a function $g: Y \rightarrow X$ such that $g \circ f = I_X$ and $f \circ g = I_Y$. The function g is called the *inverse of f* and is denoted by f^{-1} .

Thus, if f is invertible, then f must be one-one and onto and conversely, if f is one-one and onto, then f must be invertible. This fact significantly helps for proving a function f to be invertible by showing that f is one-one and onto, specially when the actual inverse of f is not to be determined.

Example 23 Let $f: \mathbb{N} \rightarrow \mathbb{N}$ be a function defined as $f(x) = x + 1$, where, $\{y \in \mathbb{N} : y = x + 1 \text{ for some } x \in \mathbb{N}\}$. Show that f is invertible. Find the inverse.

Solution Consider an arbitrary element y of \mathbb{N} . By the definition of f , $y = x + 1$, for some x in the domain \mathbb{N} . This shows that $x = \frac{(y-1)}{1}$. Define $g: \mathbb{N} \rightarrow \mathbb{N}$ by

$$g(y) = \frac{(y-1)}{1}. \text{ Now, } g \circ f(x) = g(f(x)) = g(x+1) = \frac{(x+1)-1}{1} = x \text{ and}$$

$$f \circ g(y) = f(g(y)) = f\left(\frac{(y-1)}{1}\right) = \frac{(y-1)}{1} + 1 = y. \text{ This shows that } g \circ f = I_X$$

and $f \circ g = I_Y$, which implies that f is invertible and g is the inverse of f .

Example 24 Let $\{n^2 : n \in \mathbb{N}\} \subset \mathbb{N}$. Consider $f: \mathbb{N} \rightarrow \mathbb{N}$ as $f(n) = n^2$. Show that f is invertible. Find the inverse of f .

Solution An arbitrary element y in \mathbb{N} is of the form n^2 , for some $n \in \mathbb{N}$. This implies that $n = \sqrt{y}$. This gives a function $g: \mathbb{N} \rightarrow \mathbb{N}$, defined by $g(y) = \sqrt{y}$. Now,

$$g \circ f(n) = g(f(n)) = g(n^2) = \sqrt{n^2} = n \text{ and } f \circ g(y) = f(\sqrt{y}) = (\sqrt{y})^2 = y, \text{ which shows that } g \circ f = I_X \text{ and } f \circ g = I_Y. \text{ Hence, } f \text{ is invertible with } f^{-1} = g.$$

Example 25 Let $f: \mathbb{N} \rightarrow \mathbb{R}$ be a function defined as $f(x) = x^2 + x$. Show that $f: \mathbb{N} \rightarrow \mathbb{R}$, where, \mathbb{R} is the range of f , is invertible. Find the inverse of f .

Solution Let y be an arbitrary element of range f . Then $y = x^2 + x$, for some

$$x \text{ in } \mathbb{N}, \text{ which implies that } y = x(x+1). \text{ This gives } x = \frac{((\sqrt{y+1/4})-1/2)}{1}, \text{ as } y \geq 0.$$

Let us define $g : \mathbb{N} \rightarrow \mathbb{N}$ by $g(y) = \frac{((\sqrt{y-1})-1)}{2}$.

Now $g \circ f(x) = g(f(x)) = g(x^2 - x) = \frac{((\sqrt{x^2 - x} - 1))}{2} = \frac{(x^2 - x - 1)}{2} = x$

and $f \circ g(y) = f\left(\frac{((\sqrt{y-1})-1)}{2}\right) = \left(\frac{((\sqrt{y-1})-1)}{2}\right)^2 - \frac{((\sqrt{y-1})-1)}{2} + y = y$.

Hence, $g \circ f = I_{\mathbb{N}}$ and $f \circ g = I_{\mathbb{N}}$. This implies that f is invertible with $f^{-1} = g$.

Example 26 Consider $f : \mathbb{N} \rightarrow \mathbb{N}$, $g : \mathbb{N} \rightarrow \mathbb{N}$ and $h : \mathbb{N} \rightarrow \mathbb{R}$ defined as $f(x) = x^2$, $g(y) = \sqrt{y}$ and $h(z) = \sin z$, $\forall x, y$ and z in \mathbb{N} . Show that $h \circ (g \circ f) = (h \circ g) \circ f$.

Solution We have

$$h \circ (g \circ f)(x) = h(g(f(x))) = h(g(x^2)) = h(\sqrt{x^2}) = h(x) = \sin(x) \quad \forall x \in \mathbb{N}.$$

Also, $((h \circ g) \circ f)(x) = (h \circ g)(f(x)) = (h \circ g)(x^2) = h(g(x^2)) = h(\sqrt{x^2}) = h(x) = \sin(x), \quad \forall x \in \mathbb{N}.$

This shows that $h \circ (g \circ f) = (h \circ g) \circ f$.

This result is true in general situation as well.

Theorem 1 If $f : X \rightarrow Y$, $g : Y \rightarrow Z$ and $h : Z \rightarrow W$ are functions, then

$$h \circ (g \circ f) = (h \circ g) \circ f.$$

Proof We have

$$h \circ (g \circ f)(x) = h(g(f(x))), \quad \forall x \in X$$

and $(h \circ g) \circ f(x) = h(g(f(x))), \quad \forall x \in X.$

Hence, $h \circ (g \circ f) = (h \circ g) \circ f$.

Example 27 Consider $f : \{1, 2, 3\} \rightarrow \{a, b, c\}$ and $g : \{a, b, c\} \rightarrow \{\text{apple, ball, cat}\}$ defined as $f(1) = a, f(2) = b, f(3) = c, g(a) = \text{apple}, g(b) = \text{ball}$ and $g(c) = \text{cat}$. Show that f, g and $g \circ f$ are invertible. Find out f^{-1}, g^{-1} and $(g \circ f)^{-1}$ and show that $(g \circ f)^{-1} = f^{-1} \circ g^{-1}$.

Solution Note that by definition, f and g are bijective functions. Let $f : \{a, b, c\} \rightarrow \{, , \}$ and $g : \{\text{apple, ball, cat}\} \rightarrow \{a, b, c\}$ be defined as $f(a) = , f(b) = , f(c) = , g(\text{apple}) = a, g(\text{ball}) = b$ and $g(\text{cat}) = c$. It is easy to verify that $f \circ f^{-1} = I_{\{, , \}}$, $f^{-1} \circ f = I_{\{a, b, c\}}$, $g \circ g^{-1} = I_{\{a, b, c\}}$ and $g^{-1} \circ g = I_{\{, , \}}$, where, $f^{-1} : \{, , \} \rightarrow \{a, b, c\}$. Now, $g \circ f : \{, , \} \rightarrow \{a, b, c\}$ is given by $g \circ f(a) = \text{apple}, g \circ f(b) = \text{ball}, g \circ f(c) = \text{cat}$. We can define

$(g \circ f)^{-1} : \{a, b, c\} \rightarrow \{, , \}$ by $(g \circ f)^{-1}(\text{apple}) = a, (g \circ f)^{-1}(\text{ball}) = b$ and $(g \circ f)^{-1}(\text{cat}) = c$. It is easy to see that $(g \circ f)^{-1} \circ (g \circ f) = I_{\{, , \}}$ and $(g \circ f) \circ (g \circ f)^{-1} = I_{\{a, b, c\}}$. Thus, we have seen that f, g and $g \circ f$ are invertible.

Now, $f \circ (g \circ f)^{-1}(\text{apple}) = f(a) = (g \circ f)^{-1}(\text{apple})$
 $f \circ (g \circ f)^{-1}(\text{ball}) = f(b) = (g \circ f)^{-1}(\text{ball})$ and
 $f \circ (g \circ f)^{-1}(\text{cat}) = f(c) = (g \circ f)^{-1}(\text{cat})$.

Hence $(g \circ f)^{-1} \circ f = \text{id}$.

The above result is true in general situation also.

Theorem 2 Let $f : X \rightarrow Y$ and $g : Y \rightarrow Z$ be two invertible functions. Then $g \circ f$ is also invertible with $(g \circ f)^{-1} = f^{-1} \circ g^{-1}$.

Proof To show that $g \circ f$ is invertible with $(g \circ f)^{-1} = f^{-1} \circ g^{-1}$, it is enough to show that $(f^{-1} \circ g^{-1}) \circ (g \circ f) = I_X$ and $(g \circ f) \circ (f^{-1} \circ g^{-1}) = I_Y$.

Now, $(f^{-1} \circ g^{-1}) \circ (g \circ f) = (f^{-1} \circ (g^{-1} \circ g)) \circ f$, by Theorem
 $(f^{-1} \circ I_Y) \circ f$, by Theorem
 $(f^{-1} \circ I_Y) \circ f = I_X$, by definition of f
 I_X .

Similarly, it can be shown that $(g \circ f) \circ (f^{-1} \circ g^{-1}) = I_Y$.

Example 28 Let $\{, , \}$. Determine whether the functions $f : \{, , \} \rightarrow \{, , \}$ defined as below have inverses. Find f^{-1} , if it exists.

- (a) $f : \{(,), (,), (,)\}$
- (b) $f : \{(,), (,), (,)\}$
- (c) $f : \{(,), (,), (,)\}$

Solution

- (a) It is easy to see that f is one-one and onto, so that f is invertible with the inverse f^{-1} of f given by $f^{-1} : \{(,), (,), (,)\} \rightarrow \{(,), (,), (,)\}$.
- (b) Since $f(,) = f(,)$, f is not one-one, so that f is not invertible.
- (c) It is easy to see that f is one-one and onto, so that f is invertible with $f^{-1} : \{(,), (,), (,)\} \rightarrow \{(,), (,), (,)\}$.

EXERCISE 1.3

1. Let $f: \{1, 2, 3\} \rightarrow \{1, 2, 3\}$ and $g: \{1, 2, 3\} \rightarrow \{1, 2, 3\}$ be given by $f = \{(1, 1), (2, 2), (3, 3)\}$ and $g = \{(1, 2), (2, 1), (3, 3)\}$. Write down $g \circ f$.
2. Let f, g and h be functions from \mathbf{R} to \mathbf{R} . Show that

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

$$(f \cdot g) \circ h = (f \circ h) \cdot (g \circ h)$$
3. Find $g \circ f$ and $f \circ g$, if
 - (i) $f(x) = x$ and $g(x) = x$
 - (ii) $f(x) = x$ and $g(x) = x^{-1}$.
4. If $f(x) = \frac{(x+1)}{(x-1)}$, $x \neq -1$, show that $f \circ f(x) = x$, for all $x \neq -1$. What is the inverse of f ?
5. State with reason whether following functions have inverse
 - (i) $f: \{1, 2, 3\} \rightarrow \{1, 2, 3\}$ with $f = \{(1, 1), (2, 2), (3, 3)\}$
 - (ii) $g: \{1, 2, 3\} \rightarrow \{1, 2, 3\}$ with $g = \{(1, 2), (2, 1), (3, 3)\}$
 - (iii) $h: \{1, 2, 3\} \rightarrow \{1, 2, 3\}$ with $h = \{(1, 2), (2, 1), (3, 3)\}$
6. Show that $f: \mathbf{R} \rightarrow \mathbf{R}$, given by $f(x) = \frac{x}{(x+1)}$ is one-one. Find the inverse of the function $f: \mathbf{R} \rightarrow \text{Range } f$.
 (Hint: or $y \in \text{Range } f, y = f(x) = \frac{x}{x+1}$, for some x in \mathbf{R} , i.e., $x = \frac{y}{1-y}$)
7. Consider $f: \mathbf{R} \rightarrow \mathbf{R}$ given by $f(x) = x$. Show that f is invertible. Find the inverse of f .
8. Consider $f: \mathbf{R}_+ \rightarrow (0, \infty)$ given by $f(x) = x$. Show that f is invertible with the inverse f^{-1} of f given by $f^{-1}(y) = \sqrt{y-1}$, where \mathbf{R} is the set of all non-negative real numbers.

9. Consider $f: \mathbf{R}_+ \rightarrow (-\infty, \infty)$ given by $f(x) = x - x^2$. Show that f is invertible

with $f^{-1}(y) = \left(\frac{(\sqrt{y+1}) - 1}{2} \right)$.

10. Let $f: X \rightarrow Y$ be an invertible function. Show that f has unique inverse.
 (Hint: suppose g and h are two inverses of f . Then for all $y \in Y$,
 $f \circ g(y) = y = f \circ h(y)$. Use one-one-ness of f .)

11. Consider $f: \{1, 2, 3\} \rightarrow \{a, b, c\}$ given by $f(1) = a, f(2) = b$ and $f(3) = c$. Find f^{-1} and show that $(f^{-1})^{-1} = f$.

12. Let $f: X \rightarrow Y$ be an invertible function. Show that the inverse of f^{-1} is f , i.e.,
 $(f^{-1})^{-1} = f$.

13. If $f: \mathbf{R} \rightarrow \mathbf{R}$ be given by $f(x) = (x - 1)^{-1}$, then $f \circ f(x)$ is

- (A) x^{-1} (B) x (C) $x - 1$ (D) $(x - 1)^{-1}$.

14. Let $f: \mathbf{R} \setminus \{-1\} \rightarrow \mathbf{R}$ be a function defined as $f(x) = \frac{x}{x+1}$. The inverse of

f is the map $g: \text{Range } f \rightarrow \mathbf{R} \setminus \{-1\}$ given by

- (A) $g(y) = \frac{y}{-y}$ (B) $g(y) = \frac{y}{-y-1}$
 (C) $g(y) = \frac{y}{-y-1}$ (D) $g(y) = \frac{y}{-y}$

1.5 Binary Operations

Right from the school days, you must have come across four fundamental operations namely addition, subtraction, multiplication and division. The main feature of these operations is that given any two numbers a and b , we associate another number $a + b$

or $a - b$ or ab or $\frac{a}{b}, b \neq 0$. It is to be noted that only two numbers can be added or multiplied at a time. When we need to add three numbers, we first add two numbers and the result is then added to the third number. Thus, addition, multiplication, subtraction

and division are examples of binary operation, as 'binary' means two. If we want to have a general definition which can cover all these four operations, then the set of numbers is to be replaced by an arbitrary set X and then general binary operation is nothing but association of any pair of elements a, b from X to another element of X . This gives rise to a general definition as follows:

Definition 10 A binary operation $*$ on a set A is a function $*$: $A \times A \rightarrow A$. e denote $*(a, b)$ by $a * b$.

Example 29 how that addition, subtraction and multiplication are binary operations on \mathbf{R} , but division is not a binary operation on \mathbf{R} . urther, show that division is a binary operation on the set \mathbf{R}_* of nonero real numbers.

Solution : $\mathbf{R} \times \mathbf{R} \rightarrow \mathbf{R}$ is given by
 $(a, b) \rightarrow a + b$
 $- : \mathbf{R} \times \mathbf{R} \rightarrow \mathbf{R}$ is given by
 $(a, b) \rightarrow a - b$
 $\times : \mathbf{R} \times \mathbf{R} \rightarrow \mathbf{R}$ is given by
 $(a, b) \rightarrow ab$

ince '+', '-' and '×' are functions, they are binary operations on \mathbf{R} .

But $\div : \mathbf{R} \times \mathbf{R} \rightarrow \mathbf{R}$, given by $(a, b) \rightarrow \frac{a}{b}$, is not a function and hence not a binary operation, as for $b = 0$, $\frac{a}{b}$ is not defined.

However, $\div : \mathbf{R}_* \times \mathbf{R}_* \rightarrow \mathbf{R}_*$, given by $(a, b) \rightarrow \frac{a}{b}$ is a function and hence a binary operation on \mathbf{R}_* .

Example 30 how that subtraction and division are not binary operations on \mathbf{N} .

Solution : $\mathbf{N} \times \mathbf{N} \rightarrow \mathbf{N}$, given by $(a, b) \rightarrow a - b$, is not binary operation, as the image of $(,)$ under '-' is $\notin \mathbf{N}$. imilarly, $\div : \mathbf{N} \times \mathbf{N} \rightarrow \mathbf{N}$, given by $(a, b) \rightarrow a \div b$ is not a binary operation, as the image of $(,)$ under \div is $\div = - \notin \mathbf{N}$.

Example 31 how that $*$: $\mathbf{R} \times \mathbf{R} \rightarrow \mathbf{R}$ given by $(a, b) \rightarrow a + b$ is a binary operation.

Solution ince '+' carries each pair (a, b) to a unique element $a + b$ in \mathbf{R} , '+' is a binary operation on \mathbf{R} .

Example 32 Let $\mathcal{P}(X)$ be the set of all subsets of a given set X . how that $\cup : \mathcal{P}(X) \times \mathcal{P}(X) \rightarrow \mathcal{P}(X)$ given by $(A, B) \rightarrow A \cup B$ and $\cap : \mathcal{P}(X) \times \mathcal{P}(X) \rightarrow \mathcal{P}(X)$ given by $(A, B) \rightarrow A \cap B$ are binary operations on the set $\mathcal{P}(X)$.

Solution since union operation \cup carries each pair (A, B) in $\mathcal{P}(X) \times \mathcal{P}(X)$ to a unique element $A \cup B$ in $\mathcal{P}(X)$, \cup is binary operation on $\mathcal{P}(X)$. Similarly, the intersection operation \cap carries each pair (A, B) in $\mathcal{P}(X) \times \mathcal{P}(X)$ to a unique element $A \cap B$ in $\mathcal{P}(X)$, \cap is a binary operation on $\mathcal{P}(X)$.

Example 33 how that the $\vee : \mathbf{R} \times \mathbf{R} \rightarrow \mathbf{R}$ given by $(a, b) \rightarrow \max \{a, b\}$ and the $\wedge : \mathbf{R} \times \mathbf{R} \rightarrow \mathbf{R}$ given by $(a, b) \rightarrow \min \{a, b\}$ are binary operations.

Solution since \vee carries each pair (a, b) in $\mathbf{R} \times \mathbf{R}$ to a unique element namely maximum of a and b lying in \mathbf{R} , \vee is a binary operation. Using the similar argument, one can say that \wedge is also a binary operation.

Remark $\vee(a, b) = \vee(b, a)$, $\wedge(a, b) = \wedge(b, a)$ and $\vee(a, \vee(b, c)) = \vee(\vee(a, b), c)$.

When number of elements in a set A is small, we can express a binary operation $*$ on the set A through a table called the *operation table* for the operation $*$. For example consider $A = \{1, 2, 3\}$. Then, the operation \vee on A defined in Example can be expressed by the following operation table (Table 1.1). Here, $\vee(1, 1) = 1$, $\vee(1, 2) = 2$, $\vee(1, 3) = 3$.

Table 1.1

V	1	2	3
1	1	2	3
2	2	2	3
3	3	3	3

Here, we are having 3 rows and 3 columns in the operation table with (i, j) the entry of the table being maximum of i^{th} and j^{th} elements of the set A . This can be generalised for general operation $* : A \times A \rightarrow A$. If $A = \{a_1, a_2, \dots, a_n\}$. Then the operation table will be having n rows and n columns with $(i, j)^{\text{th}}$ entry being $a_i * a_j$. Conversely, given any operation table having n rows and n columns with each entry being an element of $A = \{a_1, a_2, \dots, a_n\}$, we can define a binary operation $* : A \times A \rightarrow A$ given by $a_i * a_j$ the entry in the i^{th} row and j^{th} column of the operation table.

We may note that addition and multiplication can be added in any order and the result is same, i.e., $a + b = b + a$ and $a \cdot b = b \cdot a$, but subtraction of a and b in different order give different results, i.e., $a - b \neq b - a$. Similarly, in case of multiplication of a and b , order is immaterial, but division of a and b in different order give different results. Thus, addition and multiplication of a and b are meaningful, but subtraction and division of a and b are meaningless. For subtraction and division we have to write ‘subtract from a ’, ‘subtract from b ’, ‘divide by a ’ or ‘divide by b ’.

This leads to the following definition:

Definition 11 A binary operation $*$ on the set X is called *commutative*, if $a * b = b * a$, for every $a, b \in X$.

Example 34 how that $+$: $\mathbf{R} \times \mathbf{R} \rightarrow \mathbf{R}$ and \times : $\mathbf{R} \times \mathbf{R} \rightarrow \mathbf{R}$ are commutative binary operations, but $-$: $\mathbf{R} \times \mathbf{R} \rightarrow \mathbf{R}$ and \div : $\mathbf{R}_* \times \mathbf{R}_* \rightarrow \mathbf{R}_*$ are not commutative.

Solution since $a + b = b + a$ and $a \times b = b \times a, \forall a, b \in \mathbf{R}$, ‘+’ and ‘ \times ’ are commutative binary operation. However, ‘-’ is not commutative, since $1 - 2 \neq 2 - 1$. imilarly, $2 \div 1 \neq 1 \div 2$ shows that ‘ \div ’ is not commutative.

Example 35 how that $*$: $\mathbf{R} \times \mathbf{R} \rightarrow \mathbf{R}$ defined by $a * b = a - b$ is not commutative.

Solution ince $1 * 2 = 1 - 2 = -1$ and $2 * 1 = 2 - 1 = 1$, showing that the operation $*$ is not commutative.

If we want to associate three elements of a set X through a binary operation on X , we encounter a natural problem. The expression $a * b * c$ may be interpreted as $(a * b) * c$ or $a * (b * c)$ and these two expressions need not be same. or example, $(1 - 2) - 3 \neq 1 - (2 - 3)$. Therefore, association of three numbers, and through the binary operation ‘subtraction’ is meaningless, unless bracket is used. But in case of addition, $1 + 2 + 3$ has the same value whether we look at it as $(1 + 2) + 3$ or as $1 + (2 + 3)$. Thus, association of or even more than numbers through addition is meaningful without using bracket. This leads to the following:

Definition 12 A binary operation $*$: $A \times A \rightarrow A$ is said to be *associative* if

$$(a * b) * c = a * (b * c), \forall a, b, c, \in A.$$

Example 36 how that addition and multiplication are associative binary operation on \mathbf{R} . But subtraction is not associative on \mathbf{R} . ivision is not associative on \mathbf{R}_* .

Solution Addition and multiplication are associative, since $(a + b) + c = a + (b + c)$ and $(a \times b) \times c = a \times (b \times c) \forall a, b, c \in \mathbf{R}$. However, subtraction and division are not associative, as $(1 - 2) - 3 \neq 1 - (2 - 3)$ and $(2 \div 1) \div 3 \neq 2 \div (1 \div 3)$.

Example 37 how that $*$: $\mathbf{R} \times \mathbf{R} \rightarrow \mathbf{R}$ given by $a * b = a - b$ is not associative.

Solution The operation $*$ is not associative, since

$$(1 *) 2) * 3 = (1 - 2) - 3 = -4,$$

while $1 * (2 *) 3 = 1 * (2 - 3) = 1 - (-1) = 2$.

Remark Associative property of a binary operation is very important in the sense that with this property of a binary operation, we can write $a * a * \dots * a_n$ which is not ambiguous. But in absence of this property, the expression $a * a * \dots * a_n$ is ambiguous unless brackets are used. Recall that in the earlier classes brackets were used whenever subtraction or division operations or more than one operation occurred.

or the binary operation ‘+’ on \mathbf{R} , the interesting feature of the number zero is that $a + 0 = a = 0 + a$, i.e., any number remains unaltered by adding zero. But in case of multiplication, the number 1 plays this role, as $a \times 1 = a = 1 \times a, \forall a \in \mathbf{R}$. This leads to the following definition:

Definition 13 Given a binary operation $*$: $A \times A \rightarrow A$, an element $e \in A$, if it exists, is called *identity* for the operation $*$, if $a * e = a = e * a, \forall a \in A$.

Example 38 Show that zero is the identity for addition on \mathbf{R} and 1 is the identity for multiplication on \mathbf{R} . But there is no identity element for the operations

$$: \mathbf{R} \times \mathbf{R} \rightarrow \mathbf{R} \text{ and } \div : \mathbf{R}_* \times \mathbf{R}_* \rightarrow \mathbf{R}_*.$$

Solution $a + 0 = a$ and $a \times 1 = a, \forall a \in \mathbf{R}$ implies that 0 and 1 are identity elements for the operations ‘+’ and ‘ \times ’ respectively. Further, there is no element e in \mathbf{R} with $a + e = e + a, \forall a$. Similarly, we can not find any element e in \mathbf{R}_* such that $a \div e = e \div a, \forall a$ in \mathbf{R}_* . Hence, ‘+’ and ‘ \div ’ do not have identity element.

Remark Zero is identity for the addition operation on \mathbf{R} but it is not identity for the addition operation on \mathbf{N} , as $0 \notin \mathbf{N}$. In fact the addition operation on \mathbf{N} does not have any identity.

One further notices that for the addition operation $+$: $\mathbf{R} \times \mathbf{R} \rightarrow \mathbf{R}$, given any $a \in \mathbf{R}$, there exists $-a$ in \mathbf{R} such that $a + (-a) = 0$ (identity for ‘+’) $(-a) + a = 0$.

Similarly, for the multiplication operation on \mathbf{R} , given any $a \neq 0$ in \mathbf{R} , we can choose $\frac{-}{a}$

in \mathbf{R} such that $a \times \frac{-}{a} = 1$ (identity for ‘ \times ’) $\frac{-}{a} \times a = 1$. This leads to the following definition:

Definition 14 Given a binary operation $*$: $A \times A \rightarrow A$ with the identity element e in A , an element $a \in A$ is said to be *invertible* with respect to the operation $*$, if there exists an element b in A such that $a * b = e = b * a$ and b is called the *inverse of a* and is denoted by a^{-1} .

Example 39 Show that $-a$ is the inverse of a for the addition operation ‘+’ on \mathbf{R} and

$\frac{-}{a}$ is the inverse of $a \neq 0$ for the multiplication operation ‘ \times ’ on \mathbf{R} .

Solution As $a + (-a) = 0 = a + (-a)$ and $(-a) + a = 0$, $-a$ is the inverse of a for addition.

Similarly, for $a \neq 0, a \times \frac{-}{a} = 1 = \frac{-}{a} \times a$ implies that $\frac{-}{a}$ is the inverse of a for multiplication.

Example 40 how that $-a$ is not the inverse of $a \in \mathbf{N}$ for the addition operation on

\mathbf{N} and $\frac{1}{a}$ is not the inverse of $a \in \mathbf{N}$ for multiplication operation \times on \mathbf{N} , for $a \neq 1$.

Solution since $-a \notin \mathbf{N}$, $-a$ can not be inverse of a for addition operation on \mathbf{N} , although $-a$ satisfies $a + (-a) = (-a) + a = 0$.

Similarly, for $a \neq 1$ in \mathbf{N} , $\frac{1}{a} \notin \mathbf{N}$, which implies that other than no element of \mathbf{N} has inverse for multiplication operation on \mathbf{N} .

Examples 1.1, 1.2, and 1.3 show that addition on \mathbf{R} is a commutative and associative binary operation with 0 as the identity element and $-a$ as the inverse of a in $\mathbf{R} \forall a$.

EXERCISE 1.4

1. Determine whether or not each of the definition of $*$ given below gives a binary operation. In the event that $*$ is not a binary operation, give justification for this.

(i) in \mathbf{Z} , define $*$ by $a * b = a + b$

(ii) in \mathbf{Z} , define $*$ by $a * b = ab$

(iii) in \mathbf{R} , define $*$ by $a * b = ab$

(iv) in \mathbf{Z} , define $*$ by $a * b = a - b$

(v) in \mathbf{Z} , define $*$ by $a * b = a$

2. For each operation $*$ defined below, determine whether $*$ is binary, commutative or associative.

(i) in \mathbf{Z} , define $a * b = a + b$

(ii) in \mathbf{Q} , define $a * b = ab$

(iii) in \mathbf{Q} , define $a * b = \frac{ab}{a+b}$

(iv) in \mathbf{Z} , define $a * b = a^b$

(v) in \mathbf{Z} , define $a * b = a^b$

(vi) in $\mathbf{R} \setminus \{0\}$, define $a * b = \frac{a}{b}$

3. Consider the binary operation \wedge on the set $\{0, 1, 2, 3\}$ defined by $a \wedge b = \min\{a, b\}$. Write the operation table of the operation \wedge .

4. Consider a binary operation $*$ on the set $\{1, 2, 3, 4, 5\}$ given by the following multiplication table (Table .).
- Compute $(2 * 3) * 4$ and $4 * (2 * 3)$
 - Is $*$ commutative
 - Compute $(2 * 3) * (4 * 5)$.
- (Hint: use the following table)

Table 1.2

$*$	1	2	3	4	5
1	1	1	1	1	1
2	1	2	1	2	1
3	1	1	3	1	1
4	1	2	1	4	1
5	1	1	1	1	5

- Let $*$ be the binary operation on the set $\{1, 2, 3, 4, 5\}$ defined by $a * b = \text{H.C.M. of } a \text{ and } b$. Is the operation $*$ same as the operation $*$ defined in Exercise above justify your answer.
 - Let $*$ be the binary operation on \mathbb{N} given by $a * b = \text{L.C.M. of } a \text{ and } b$. and
 - $*$, $*$ (ii) Is $*$ commutative
 - Is $*$ associative (iv) and the identity of $*$ in \mathbb{N}
 - Which elements of \mathbb{N} are invertible for the operation $*$
 - Is $*$ defined on the set $\{1, 2, 3, 4, 5\}$ by $a * b = \text{L.C.M. of } a \text{ and } b$ a binary operation justify your answer.
 - Let $*$ be the binary operation on \mathbb{N} defined by $a * b = \text{H.C.M. of } a \text{ and } b$. Is $*$ commutative Is $*$ associative does there exist identity for this binary operation on \mathbb{N}
 - Let $*$ be a binary operation on the set \mathbb{Q} of rational numbers as follows:
 - $a * b = a + b$ (ii) $a * b = a - b$
 - $a * b = a \cdot ab$ (iv) $a * b = (a + b)$
 - $a * b = \frac{ab}{a+b}$ (vi) $a * b = ab$
- and which of the binary operations are commutative and which are associative.
- and which of the operations given above has identity.
 - Let $A = \mathbb{N} \times \mathbb{N}$ and $*$ be the binary operation on A defined by

$$(a, b) * (c, d) = (a + c, b + d)$$

how that $*$ is commutative and associative. Find the identity element for $*$ on A , if any.

12. State whether the following statements are true or false. Justify.
- (i) For an arbitrary binary operation $*$ on a set N , $a * a = a \forall a \in N$.
 - (ii) If $*$ is a commutative binary operation on N , then $a * (b * c) = (c * b) * a$
13. Consider a binary operation $*$ on N defined as $a * b = a + b$. Choose the correct answer.
- (A) Is $*$ both associative and commutative
 - (B) Is $*$ commutative but not associative
 - (C) Is $*$ associative but not commutative
 - (D) Is $*$ neither commutative nor associative

Miscellaneous Examples

Example 41 If R_1 and R_2 are equivalence relations in a set A , show that $R_1 \cap R_2$ is also an equivalence relation.

Solution Since R_1 and R_2 are equivalence relations, $(a, a) \in R_1$ and $(a, a) \in R_2 \forall a \in A$. This implies that $(a, a) \in R_1 \cap R_2, \forall a$, showing $R_1 \cap R_2$ is reflexive. Further, $(a, b) \in R_1 \cap R_2 \Rightarrow (a, b) \in R_1$ and $(a, b) \in R_2 \Rightarrow (b, a) \in R_1$ and $(b, a) \in R_2 \Rightarrow (b, a) \in R_1 \cap R_2$, hence, $R_1 \cap R_2$ is symmetric. Similarly, $(a, b) \in R_1 \cap R_2$ and $(b, c) \in R_1 \cap R_2 \Rightarrow (a, c) \in R_1$ and $(a, c) \in R_2 \Rightarrow (a, c) \in R_1 \cap R_2$. This shows that $R_1 \cap R_2$ is transitive. Thus, $R_1 \cap R_2$ is an equivalence relation.

Example 42 Let R be a relation on the set A of ordered pairs of positive integers defined by $(x, y) R (u, v)$ if and only if $xv = yu$. Show that R is an equivalence relation.

Solution Clearly, $(x, y) R (x, y), \forall (x, y) \in A$, since $xy = yx$. This shows that R is reflexive. Further, $(x, y) R (u, v) \Rightarrow xv = yu \Rightarrow uy = vx$ and hence $(u, v) R (x, y)$. This shows that R is symmetric. Similarly, $(x, y) R (u, v)$ and $(u, v) R (a, b) \Rightarrow xv = yu$ and

$ub = va \Rightarrow xv \frac{a}{u} = yu \frac{a}{u} \Rightarrow xv \frac{b}{v} = yu \frac{a}{u} \Rightarrow xb = ya$ and hence $(x, y) R (a, b)$. Thus, R is transitive. Thus, R is an equivalence relation.

Example 43 Let $X = \{1, 2, 3, 4, 5, 6, 7, 8, 9, 10\}$. Let R_1 be a relation in X given by $R_1 = \{(x, y) : x \text{ is divisible by } y\}$ and R_2 be another relation on X given by $R_2 = \{(x, y) : \{x, y\} \subset \{1, 2, 3, 4, 5, 6, 7, 8, 9, 10\}\}$ or $\{x, y\} \subset \{1, 2, 3, 4, 5, 6, 7, 8, 9, 10\}$. Show that $R_1 \cap R_2$ is an equivalence relation.

Solution Note that the characteristic of sets $\{2, 4, 6, \dots\}$, $\{3, 6, 9, \dots\}$ and $\{4, 8, 12, \dots\}$ is that difference between any two elements of these sets is a multiple of 2. Therefore, $(x, y) \in R \Rightarrow x - y$ is a multiple of 2 $\Rightarrow \{x, y\} \subset \{2, 4, 6, \dots\}$ or $\{x, y\} \subset \{3, 6, 9, \dots\}$ or $\{x, y\} \subset \{4, 8, 12, \dots\} \Rightarrow (x, y) \in R$. Hence, $R \subset R$. Similarly, $\{x, y\} \in R \Rightarrow \{x, y\} \subset \{2, 4, 6, \dots\}$ or $\{x, y\} \subset \{3, 6, 9, \dots\}$ or $\{x, y\} \subset \{4, 8, 12, \dots\} \Rightarrow x - y$ is divisible by 2 $\Rightarrow \{x, y\} \in R$. This shows that $R \subset R$. Hence, $R = R$.

Example 44 Let $f: X \rightarrow Y$ be a function. Define a relation R in X given by $R = \{(a, b) : f(a) = f(b)\}$. Examine whether R is an equivalence relation or not.

Solution For every $a \in X$, $(a, a) \in R$, since $f(a) = f(a)$, showing that R is reflexive. Similarly, $(a, b) \in R \Rightarrow f(a) = f(b) \Rightarrow f(b) = f(a) \Rightarrow (b, a) \in R$. Therefore, R is symmetric. Further, $(a, b) \in R$ and $(b, c) \in R \Rightarrow f(a) = f(b)$ and $f(b) = f(c) \Rightarrow f(a) = f(c) \Rightarrow (a, c) \in R$, which implies that R is transitive. Hence, R is an equivalence relation.

Example 45 Determine which of the following binary operations on the set R are associative and which are commutative.

(a) $a * b = a + b \quad \forall a, b \in R$ (b) $a * b = \frac{(a+b)}{2} \quad \forall a, b \in R$

Solution

(a) Clearly, by definition $a * b = b * a$, $\forall a, b \in R$. Also $(a * b) * c = (a + b) + c$ and $a * (b * c) = a + (b + c)$, $\forall a, b, c \in R$. Hence R is both associative and commutative.

(b) $a * b = \frac{a+b}{2} = \frac{b+a}{2} = b * a$, shows that $*$ is commutative. Further,

$$(a * b) * c = \left(\frac{a+b}{2} \right) * c = \frac{\left(\frac{a+b}{2} \right) + c}{2} = \frac{a+b+c}{4}.$$

But $a * (b * c) = a * \left(\frac{b+c}{2} \right) = \frac{a + \frac{b+c}{2}}{2} = \frac{a+b+c}{4} \neq \frac{a+b+c}{4}$ in general.

Hence, $*$ is not associative.

Example 46 Find the number of all one-one functions from set $A = \{1, 2, 3\}$ to itself.

Solution A one-one function from $\{1, 2, 3\}$ to itself is simply a permutation on three symbols $1, 2, 3$. Therefore, total number of one-one maps from $\{1, 2, 3\}$ to itself is same as total number of permutations on three symbols $1, 2, 3$, which is $3!$.

Example 47 Let $A = \{1, 2, 3\}$. Then show that the number of relations containing $(1, 1)$ and $(2, 2)$ which are reflexive and transitive but not symmetric is three.

Solution The smallest relation R containing $(1, 1)$ and $(2, 2)$ which is reflexive and transitive but not symmetric is $\{(1, 1), (2, 2), (3, 3), (1, 2), (2, 1), (1, 3), (3, 1)\}$. Now, if we add the pair $(2, 3)$ to R to get R' , then the relation R' will be reflexive, transitive but not symmetric. Similarly, we can obtain R'' by adding $(3, 2)$ to R to get the desired relation. However, we can not add two pairs $(2, 3), (3, 2)$ or single pair $(2, 3)$ to R at a time, as by doing so, we will be forced to add the remaining pair in order to maintain transitivity and in the process, the relation will become symmetric also which is not required. Thus, the total number of desired relations is three.

Example 48 Show that the number of equivalence relation in the set $\{1, 2, 3\}$ containing $(1, 2)$ and $(2, 3)$ is two.

Solution The smallest equivalence relation R containing $(1, 2)$ and $(2, 3)$ is $\{(1, 1), (2, 2), (3, 3), (1, 2), (2, 1), (2, 3), (3, 2), (1, 3), (3, 1)\}$. Now we are left with only pairs namely $(1, 2), (2, 1), (2, 3)$ and $(3, 2)$. If we add any one, say $(1, 2)$ to R , then for symmetry we must add $(2, 1)$ also and now for transitivity we are forced to add $(1, 3)$ and $(3, 1)$. Thus, the only equivalence relation bigger than R is the universal relation. This shows that the total number of equivalence relations containing $(1, 2)$ and $(2, 3)$ is two.

Example 49 Show that the number of binary operations on $\{1, 2\}$ having 1 as identity and having 2 as the inverse of 1 is exactly one.

Solution A binary operation $*$ on $\{1, 2\}$ is a function from $\{1, 2\} \times \{1, 2\}$ to $\{1, 2\}$, i.e., a function from $\{(1, 1), (1, 2), (2, 1), (2, 2)\} \rightarrow \{1, 2\}$. Since 1 is the identity for the desired binary operation $*$, $1 * 1 = 1, 1 * 2 = 2, 2 * 1 = 1, 2 * 2 = 2$, and the only choice left is for the pair $(2, 2)$. Since 2 is the inverse of 1, i.e., $1 * 2 = 2 * 1 = 1$, must be equal to 1. Thus, the number of desired binary operation is only one.

Example 50 Consider the identity function $I_{\mathbb{N}} : \mathbb{N} \rightarrow \mathbb{N}$ defined as $I_{\mathbb{N}}(x) = x \forall x \in \mathbb{N}$. Show that although $I_{\mathbb{N}}$ is onto but $I_{\mathbb{N}} \circ I_{\mathbb{N}} : \mathbb{N} \rightarrow \mathbb{N}$ defined as

$$(I_{\mathbb{N}} \circ I_{\mathbb{N}})(x) = I_{\mathbb{N}}(I_{\mathbb{N}}(x)) = I_{\mathbb{N}}(x) = x \quad x \in \mathbb{N} \quad x \text{ is not onto.}$$

Solution Clearly $I_{\mathbb{N}}$ is onto. But $I_{\mathbb{N}} \circ I_{\mathbb{N}}$ is not onto, as we can find an element in the co-domain \mathbb{N} such that there does not exist any x in the domain \mathbb{N} with $(I_{\mathbb{N}} \circ I_{\mathbb{N}})(x) = x$.

Example 51 Consider a function $f : \left[0, \frac{\pi}{2}\right] \rightarrow \mathbf{R}$ given by $f(x) = \sin x$ and $g : \left[0, \frac{\pi}{2}\right] \rightarrow \mathbf{R}$ given by $g(x) = \cos x$. Show that f and g are one-one, but $f \circ g$ is not one-one.

Solution Since for any two distinct elements x and y in $\left[0, \frac{\pi}{2}\right]$, $\sin x \neq \sin y$ and $\cos x \neq \cos y$, both f and g must be one-one. But $(f \circ g)(0) = \sin \cos 0 = \sin 1$ and $(f \circ g)\left(\frac{\pi}{2}\right) = \sin \frac{\pi}{2} + \cos \frac{\pi}{2} = 1 + 0 = 1$. Therefore, $f \circ g$ is not one-one.

Miscellaneous Exercise on Chapter 1

1. Let $f : \mathbf{R} \rightarrow \mathbf{R}$ be defined as $f(x) = x^2$. Find the function $g : \mathbf{R} \rightarrow \mathbf{R}$ such that $g \circ f = f \circ g$.
2. Let $f : \mathbf{Z} \rightarrow \mathbf{Z}$ be defined as $f(n) = n$, if n is odd and $f(n) = n + 1$, if n is even. Show that f is invertible. Find the inverse of f . Here, \mathbf{Z} is the set of all whole numbers.
3. If $f : \mathbf{R} \rightarrow \mathbf{R}$ is defined by $f(x) = x^2 + x$, find $f(f(x))$.
4. Show that the function $f : \mathbf{R} \rightarrow \{x \in \mathbf{R} : x > 0\}$ defined by $f(x) = \frac{x}{1+x}$, $x \in \mathbf{R}$ is one-one and onto function.
5. Show that the function $f : \mathbf{R} \rightarrow \mathbf{R}$ given by $f(x) = x^2$ is injective.
6. Give examples of two functions $f : \mathbf{N} \rightarrow \mathbf{Z}$ and $g : \mathbf{Z} \rightarrow \mathbf{Z}$ such that $g \circ f$ is injective but g is not injective.
(Hint : Consider $f(x) = x$ and $g(x) = x^2$).
7. Give examples of two functions $f : \mathbf{N} \rightarrow \mathbf{N}$ and $g : \mathbf{N} \rightarrow \mathbf{N}$ such that $g \circ f$ is onto but f is not onto.
(Hint : Consider $f(x) = x$ and $g(x) = \begin{cases} x & \text{if } x > 0 \\ 0 & \text{if } x = 0 \end{cases}$).
8. Given a non empty set X , consider $\mathcal{P}(X)$ which is the set of all subsets of X .

define the relation R in (X) as follows:

or subsets A, B in (X), ARB if and only if $A \subset B$. Is R an equivalence relation on (X) justify your answer.

9. Given a non-empty set X, consider the binary operation $*$: $(X) \times (X) \rightarrow (X)$ given by $A * B = A \cap B \forall A, B$ in (X), where (X) is the power set of X. Show that X is the identity element for this operation and X is the only invertible element in (X) with respect to the operation $*$.

10. Find the number of all onto functions from the set $\{1, 2, \dots, n\}$ to itself.

11. Let $S = \{a, b, c\}$ and $T = \{1, 2\}$. Find the number of the following functions from S to T, if it exists.

- (i) $\{(a, 1), (b, 1), (c, 1)\}$
- (ii) $\{(a, 1), (b, 2), (c, 2)\}$

12. Consider the binary operations $*$: $\mathbf{R} \times \mathbf{R} \rightarrow \mathbf{R}$ and \circ : $\mathbf{R} \times \mathbf{R} \rightarrow \mathbf{R}$ defined as $a * b = a + b$ and $a \circ b = ab, \forall a, b \in \mathbf{R}$. Show that $*$ is commutative but not associative, \circ is associative but not commutative. Further, show that $\forall a, b, c \in \mathbf{R}, a * (b \circ c) = (a * b) \circ (a * c)$. If it is so, we say that the operation $*$ distributes over the operation \circ . Does \circ distribute over $*$ justify your answer.

13. Given a non-empty set X, let $*$: $(X) \times (X) \rightarrow (X)$ be defined as $A * B = (A \cap B) \cup (B \cap A), \forall A, B \in (X)$. Show that the empty set ϕ is the identity for the operation $*$ and all the elements A of (X) are invertible with $A^{-1} = A$. (Hint : $(A \cap \phi) \cup (\phi \cap A) = A$ and $(A \cap A) \cup (A \cap A) = A * A = \phi$).

14. Define a binary operation $*$ on the set $\{1, 2, 3, 4, 5\}$ as

$$a * b = \begin{cases} a + b, & \text{if } a + b < 6 \\ a + b - 6 & \text{if } a + b \geq 6 \end{cases}$$

Show that 0 is the identity for this operation and each element $a \neq 0$ of the set is invertible with $6 - a$ being the inverse of a .

15. Let $A = \{1, 2, 3\}, B = \{1, 2, 3\}$ and $f, g : A \rightarrow B$ be functions defined

by $f(x) = x, x \in A$ and $g(x) = \begin{cases} 1 & \text{if } x = 1 \\ 2 & \text{if } x = 2 \\ 3 & \text{if } x = 3 \end{cases} x \in A$. Are f and g equal

justify your answer. (Hint: one may note that two functions $f : A \rightarrow B$ and $g : A \rightarrow B$ such that $f(a) = g(a) \forall a \in A$, are called equal functions).

16. Let $A = \{1, 2\}$. Then number of relations containing (1, 1) and (2, 2) which are reflexive and symmetric but not transitive is

- (A) 1 (B) 2 (C) 3

17. Let $A = \{1, 2\}$. Then number of equivalence relations containing (1, 1) is

- (A) 1 (B) 2 (C) 3

18. Let $f: \mathbf{R} \rightarrow \mathbf{R}$ be the signum function defined as

$$f(x) = \begin{cases} 1, & x > 0 \\ 0, & x = 0 \\ -1, & x < 0 \end{cases}$$

and $g: \mathbf{R} \rightarrow \mathbf{R}$ be the greatest Integer function given by $g(x) = \lfloor x \rfloor$, where $\lfloor x \rfloor$ is the greatest integer less than or equal to x . Then, does $f \circ g$ and $g \circ f$ coincide in \mathbf{R} ?

19. Number of binary operations on the set $\{ a, b \}$ are
 (A) 1 (B) 2 (C) 3 (D) 4

Summary

In this chapter, we studied different types of relations and equivalence relation, composition of functions, invertible functions and binary operations. The main features of this chapter are as follows:

- ◆ *Empty relation* is the relation R in X given by $R = \emptyset \subset X \times X$.
- ◆ *Universal relation* is the relation R in X given by $R = X \times X$.
- ◆ *Reflexive relation* R in X is a relation with $(a, a) \in R \quad \forall a \in X$.
- ◆ *Symmetric relation* R in X is a relation satisfying $(a, b) \in R$ implies $(b, a) \in R$.
- ◆ *Transitive relation* R in X is a relation satisfying $(a, b) \in R$ and $(b, c) \in R$ implies that $(a, c) \in R$.
- ◆ *Equivalence relation* R in X is a relation which is reflexive, symmetric and transitive.
- ◆ *Equivalence class* a containing $a \in X$ for an equivalence relation R in X is the subset of X containing all elements b related to a .
- ◆ A function $f: X \rightarrow Y$ is *one-one* (or *injective*) if $f(x) = f(x') \Rightarrow x = x' \quad \forall x, x' \in X$.
- ◆ A function $f: X \rightarrow Y$ is *onto* (or *surjective*) if given any $y \in Y, \exists x \in X$ such that $f(x) = y$.
- ◆ A function $f: X \rightarrow Y$ is *one-one and onto* (or *bijjective*), if f is both one-one and onto.
- ◆ The *composition* of functions $f: A \rightarrow B$ and $g: B \rightarrow C$ is the function $g \circ f: A \rightarrow C$ given by $g \circ f(x) = g(f(x)) \quad \forall x \in A$.
- ◆ A function $f: X \rightarrow Y$ is *invertible* if $\exists g: Y \rightarrow X$ such that $g \circ f = I_X$ and $f \circ g = I_Y$.
- ◆ A function $f: X \rightarrow Y$ is *invertible* if and only if f is one-one and onto.

- ◆ Given a finite set X , a function $f: X \rightarrow X$ is one-one (respectively onto) if and only if f is onto (respectively one-one). This is the characteristic property of a finite set. This is not true for infinite set
- ◆ A **binary operation** $*$ on a set A is a function $*$ from $A \times A$ to A .
- ◆ An element $e \in X$ is the **identity** element for binary operation $*$: $X \times X \rightarrow X$, if $a * e = a = e * a \forall a \in X$.
- ◆ An element $a \in X$ is **invertible** for binary operation $*$: $X \times X \rightarrow X$, if there exists $b \in X$ such that $a * b = e = b * a$ where, e is the identity for the binary operation $*$. The element b is called **inverse** of a and is denoted by a^{-1} .
- ◆ An operation $*$ on X is **commutative** if $a * b = b * a \forall a, b$ in X .
- ◆ An operation $*$ on X is **associative** if $(a * b) * c = a * (b * c) \forall a, b, c$ in X .

Historical Note

The concept of function has evolved over a long period of time starting from R. Descartes (-), who used the word 'function' in his manuscript *Geometrie* in 1637 to mean some positive integral power x^n of a variable x while studying geometrical curves like hyperbola, parabola and ellipse. James Gregory (-) in his work *Vera Circuli et Hyperbolae Quadratura* (1644) considered function as a quantity obtained from other quantities by successive use of algebraic operations or by any other operations. Later . . . Leibniz (-) in his manuscript *Methodus tangentium inversa, seu de functionibus* written in 1684 used the word 'function' to mean a quantity varying from point to point on a curve such as the coordinates of a point on the curve, the slope of the curve, the tangent and the normal to the curve at a point. However, in his manuscript *Historia* (1686), Leibniz used the word 'function' to mean quantities that depend on a variable. He was the first to use the phrase 'function of x '. John Bernoulli (-) used the notation ϕx for the first time in 1691 to indicate a function of x . But the general adoption of symbols like $f, \phi, \psi \dots$ to represent functions was made by Leonhard Euler (-) in 1748 in the first part of his manuscript *Analysis Insectorum*. Later on, Joseph Louis Lagrange (-) published his manuscripts *Theorie des fonctions analytiques* in 1795, where he discussed about analytic function and used the notation $f(x), \phi(x), \psi(x)$ etc. for different function of x . Subsequently, Joseph Fourier (-) gave the definition of function which was being used till the set theoretic definition of function presently used, was given after set theory was developed by Georg Cantor (-). The set theoretic definition of function known to us presently is simply an abstraction of the definition given by Fourier in a rigorous manner.



INVERSE TRIGONOMETRIC FUNCTIONS

❖ *Mathematics, in general, is fundamentally the science of self-evident things. — FELIX KLEIN* ❖

2.1 Introduction

In Chapter 1, we have studied that the inverse of a function f , denoted by f^{-1} , exists if f is one-one and onto. There are many functions which are not one-one, onto or both and hence we can not talk of their inverses. In Class XI, we studied that trigonometric functions are not one-one and onto over their natural domains and ranges and hence their inverses do not exist. In this chapter, we shall study about the restrictions on domains and ranges of trigonometric functions which ensure the existence of their inverses and observe their behaviour through graphical representations. Besides, some elementary properties will also be discussed.



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The inverse trigonometric functions play an important role in calculus for they serve to define many integrals. The concepts of inverse trigonometric functions is also used in science and engineering.

2.2 Basic Concepts

In Class XI, we have studied trigonometric functions, which are defined as follows:

sine function, i.e., $\sin : \mathbf{R} \rightarrow [-1, 1]$

cosine function, i.e., $\cos : \mathbf{R} \rightarrow [-1, 1]$

tangent function, i.e., $\tan : \mathbf{R} - \left\{ x : x = (2n + 1) \frac{\pi}{2}, n \in \mathbf{Z} \right\} \rightarrow \mathbf{R}$

cotangent function, i.e., $\cot : \mathbf{R} - \{ x : x = n\pi, n \in \mathbf{Z} \} \rightarrow \mathbf{R}$

secant function, i.e., $\sec : \mathbf{R} - \left\{ x : x = (2n + 1) \frac{\pi}{2}, n \in \mathbf{Z} \right\} \rightarrow \mathbf{R} - (-1, 1)$

cosecant function, i.e., $\operatorname{cosec} : \mathbf{R} - \{ x : x = n\pi, n \in \mathbf{Z} \} \rightarrow \mathbf{R} - (-1, 1)$

We have also learnt in Chapter 1 that if $f: X \rightarrow Y$ such that $f(x) = y$ is one-one and onto, then we can define a unique function $g: Y \rightarrow X$ such that $g(y) = x$, where $x \in X$ and $y = f(x)$, $y \in Y$. Here, the domain of $g = \text{range of } f$ and the range of $g = \text{domain of } f$. The function g is called the inverse of f and is denoted by f^{-1} . Further, g is also one-one and onto and inverse of g is f . Thus, $g^{-1} = (f^{-1})^{-1} = f$. We also have

$$(f^{-1} \circ f)(x) = f^{-1}(f(x)) = f^{-1}(y) = x$$

and $(f \circ f^{-1})(y) = f(f^{-1}(y)) = f(x) = y$

Since the domain of sine function is the set of all real numbers and range is the closed interval $[-1, 1]$. If we restrict its domain to $\left[-\frac{\pi}{2}, \frac{\pi}{2}\right]$, then it becomes one-one and onto with range $[-1, 1]$. Actually, sine function restricted to any of the intervals

$$\left[-\frac{\pi}{2}, -\frac{\pi}{2}\right], \left[-\frac{\pi}{2}, \frac{\pi}{2}\right], \left[\frac{\pi}{2}, \frac{\pi}{2}\right] \text{ etc., is one-one and its range is } [-1, 1].$$

We can, therefore, define the inverse of sine function in each of these intervals. We denote the inverse of sine function by \sin^{-1} (arc sine function). Thus, \sin^{-1} is a function whose

domain is $[-1, 1]$ and range could be any of the intervals $\left[-\frac{\pi}{2}, -\frac{\pi}{2}\right]$, $\left[-\frac{\pi}{2}, \frac{\pi}{2}\right]$ or

$\left[\frac{\pi}{2}, \frac{\pi}{2}\right]$, and so on. Corresponding to each such interval, we get a *branch* of the

function \sin^{-1} . The branch with range $\left[-\frac{\pi}{2}, \frac{\pi}{2}\right]$ is called the *principal value branch*, whereas other intervals as range give different branches of \sin^{-1} . When we refer to the function \sin^{-1} , we take it as the function whose domain is $[-1, 1]$ and range is

$$\left[-\frac{\pi}{2}, \frac{\pi}{2}\right]. \text{ We write } \sin^{-1}: [-1, 1] \rightarrow \left[-\frac{\pi}{2}, \frac{\pi}{2}\right]$$

From the definition of the inverse functions, it follows that $\sin(\sin^{-1} x) = x$ if $-1 \leq x \leq 1$ and $\sin^{-1}(\sin x) = x$ if $-\frac{\pi}{2} \leq x \leq \frac{\pi}{2}$. In other words, if $y = \sin^{-1} x$, then $\sin y = x$.

Remarks

- (i) We know from Chapter 1, that if $y = f(x)$ is an invertible function, then $x = f^{-1}(y)$. Thus, the graph of \sin^{-1} function can be obtained from the graph of original function by interchanging x and y axes, i.e., if (a, b) is a point on the graph of sine function, then (b, a) becomes the corresponding point on the graph of inverse

of sine function. Thus, the graph of the function $y = \sin^{-1} x$ can be obtained from the graph of $y = \sin x$ by interchanging x and y axes. The graphs of $y = \sin x$ and $y = \sin^{-1} x$ are as given in fig 2.1 (i), (ii), (iii). The dark portion of the graph of $y = \sin^{-1} x$ represent the principal value branch.

- (ii) It can be shown that the graph of an inverse function can be obtained from the corresponding graph of original function as a mirror image (i.e., reflection) along the line $y = x$. This can be visualised by looking the graphs of $y = \sin x$ and $y = \sin^{-1} x$ as given in the same axes (ig 2.1 (iii)).

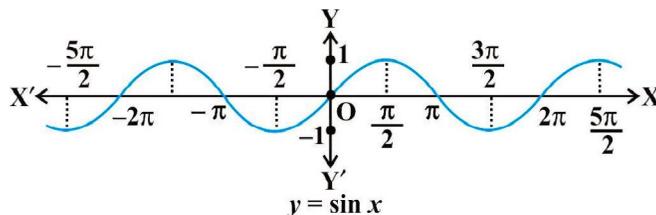


Fig 2.1 (i)

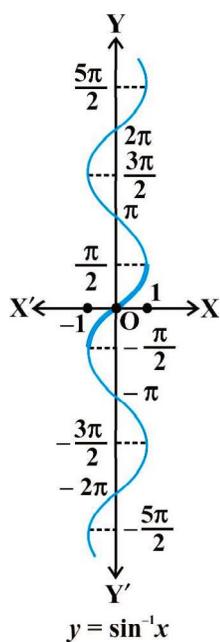


Fig 2.1 (ii)

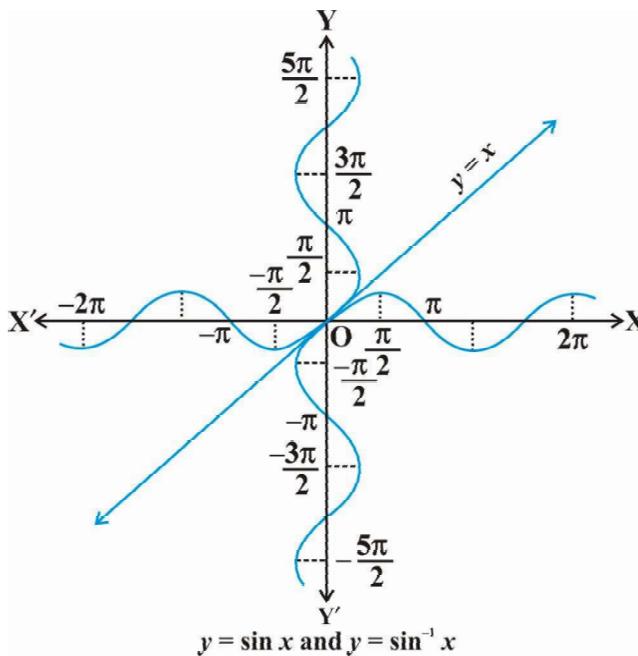


Fig 2.1 (iii)

like sine function, the cosine function is a function whose domain is the set of all real numbers and range is the set $[-1, 1]$. If we restrict the domain of cosine function to $[0, \pi]$, then it becomes one-one and onto with range $[-1, 1]$. ctually, cosine function

restricted to any of the intervals $[-\pi, \pi]$, $[\pi, 2\pi]$ etc., is bijective with range as $[-1, 1]$. We can, therefore, define the inverse of cosine function in each of these intervals. We denote the inverse of the cosine function by \cos^{-1} (arc cosine function). Thus, \cos^{-1} is a function whose domain is $[-1, 1]$ and range could be any of the intervals $[-\pi, \pi]$, $[\pi, 2\pi]$ etc. Corresponding to each such interval, we get a branch of the function \cos^{-1} . The branch with range $[-\pi, \pi]$ is called the *principal value branch* of the function \cos^{-1} . We write

$$\cos^{-1} : [-1, 1] \rightarrow [-\pi, \pi].$$

The graph of the function given by $y = \cos^{-1} x$ can be drawn in the same way as discussed about the graph of $y = \sin^{-1} x$. The graphs of $y = \cos x$ and $y = \cos^{-1} x$ are given in fig 2.2 (i) and (ii).

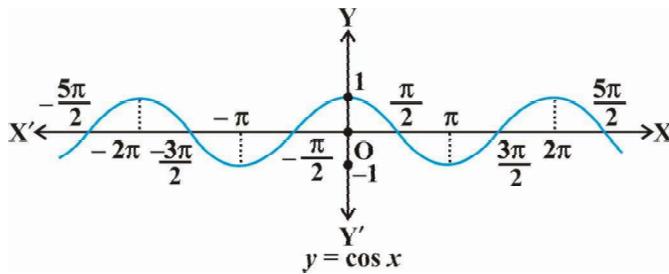


Fig 2.2 (i)

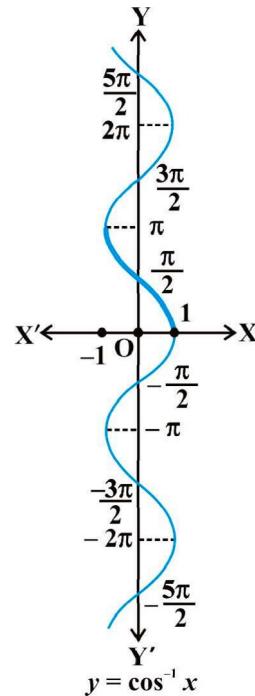


Fig 2.2 (ii)

Let us now discuss $\operatorname{cosec}^{-1} x$ and $\sec^{-1} x$ as follows:

Since, $\operatorname{cosec} x = \frac{1}{\sin x}$, the domain of the cosec function is the set $\{x : x \in \mathbf{R} \text{ and } x \neq n\pi, n \in \mathbf{Z}\}$ and the range is the set $\{y : y \in \mathbf{R}, y \geq 1 \text{ or } y \leq -1\}$ i.e., the set $\mathbf{R} - (-1, 1)$. It means that $y = \operatorname{cosec} x$ assumes all real values except $-1 < y < 1$ and is not defined for integral multiple of π . If we restrict the domain of cosec function to

$\left[-\frac{\pi}{2}, \frac{\pi}{2}\right] - \{0\}$, then it is one to one and onto with its range as the set $\mathbf{R} - (-1, 1)$. Actually,

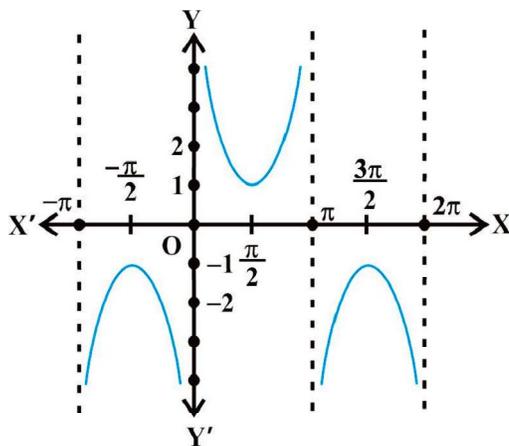
cosec function restricted to any of the intervals $\left[-\frac{\pi}{2}, -\frac{\pi}{2}\right] - \{-\pi\}$, $\left[-\frac{\pi}{2}, \frac{\pi}{2}\right] - \{0\}$,

$\left[\frac{\pi}{2}, \frac{\pi}{2}\right] - \{\pi\}$ etc., is bijective and its range is the set of all real numbers $\mathbf{R} - (-1, 1)$.

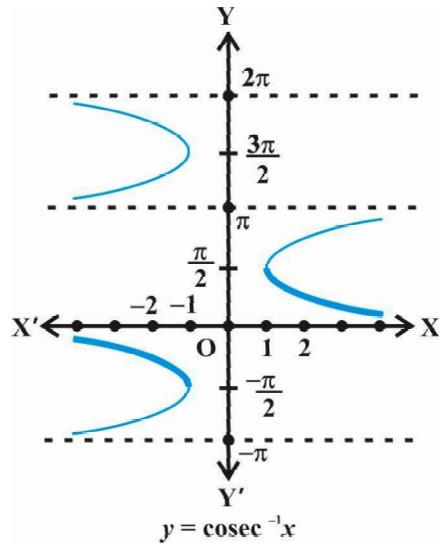
Thus $\operatorname{cosec}^{-1}$ can be defined as a function whose domain is $\mathbf{R} - (-1, 1)$ and range could be any of the intervals $\left[\frac{-\pi}{2}, \frac{\pi}{2}\right] - \{0\}$, $\left[\frac{-\pi}{2}, \frac{-\pi}{2}\right] - \{-\pi\}$, $\left[\frac{\pi}{2}, \frac{\pi}{2}\right] - \{\pi\}$ etc. The function corresponding to the range $\left[\frac{-\pi}{2}, \frac{\pi}{2}\right] - \{0\}$ is called the *principal value branch* of $\operatorname{cosec}^{-1}$. It thus has principal branch as

$$\operatorname{cosec}^{-1} : \mathbf{R} - (-1, 1) \rightarrow \left[\frac{-\pi}{2}, \frac{\pi}{2}\right] - \{0\}$$

The graphs of $y = \operatorname{cosec} x$ and $y = \operatorname{cosec}^{-1} x$ are given in fig 2. (i), (ii).



$y = \operatorname{cosec} x$
Fig 2.3 (i)



$y = \operatorname{cosec}^{-1} x$
Fig 2.3 (ii)

Also, since $\sec x = \frac{1}{\cos x}$, the domain of $y = \sec x$ is the set $\mathbf{R} - \{x : x = (2n + 1) \frac{\pi}{2}, n \in \mathbf{Z}\}$ and range is the set $\mathbf{R} - (-1, 1)$. It means that \sec (secant function) assumes all real values except $-1 < y < 1$ and is not defined for odd multiples of $\frac{\pi}{2}$. If we restrict the domain of secant function to $[\frac{-\pi}{2}, \frac{\pi}{2}] - \{0\}$, then it is one-one and onto with

its range as the set $\mathbf{R} - (-1, 1)$. Actually, secant function restricted to any of the intervals $[-\pi,] - \{\frac{-\pi}{2}\}, [, \pi] - \{\frac{\pi}{2}\}, [\pi, 2\pi] - \{\frac{\pi}{2}\}$ etc., is bijective and its range is $\mathbf{R} - \{-1, 1\}$. Thus \sec^{-1} can be defined as a function whose domain is $\mathbf{R} - (-1, 1)$ and range could be any of the intervals $[-\pi,] - \{\frac{-\pi}{2}\}, [, \pi] - \{\frac{\pi}{2}\}, [\pi, 2\pi] - \{\frac{\pi}{2}\}$ etc. Corresponding to each of these intervals, we get different branches of the function \sec^{-1} . The branch with range $[, \pi] - \{\frac{\pi}{2}\}$ is called the *principal value branch* of the function \sec^{-1} . We thus have

$$\sec^{-1} : \mathbf{R} - (-1, 1) \rightarrow [, \pi] - \{\frac{\pi}{2}\}$$

The graphs of the functions $y = \sec x$ and $y = \sec^{-1} x$ are given in fig 2. (i), (ii).

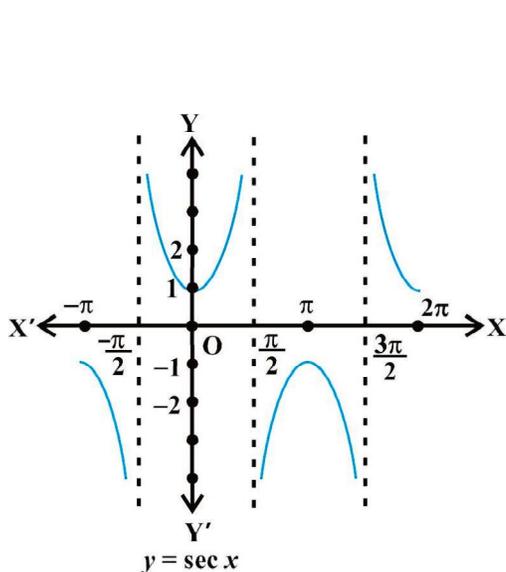


Fig 2.4 (i)

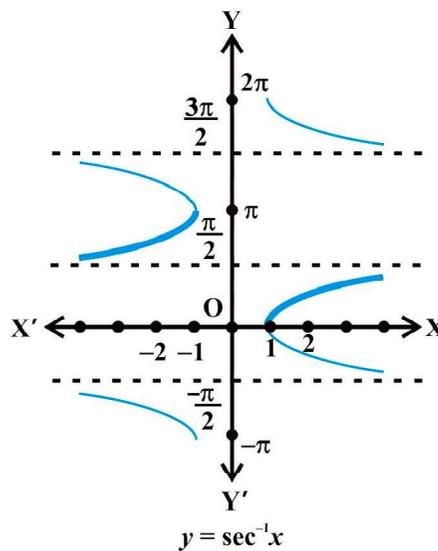


Fig 2.4 (ii)

inally, we now discuss \tan^{-1} and \cot^{-1}

we know that the domain of the tan function (tangent function) is the set

$\{x : x \in \mathbf{R} \text{ and } x \neq (2n + 1) \frac{\pi}{2}, n \in \mathbf{Z}\}$ and the range is \mathbf{R} . It means that tan function

is not defined for odd multiples of $\frac{\pi}{2}$. If we restrict the domain of tangent function to

$\left(-\frac{\pi}{2}, \frac{\pi}{2}\right)$, then it is one-one and onto with its range as \mathbf{R} . ctually, tangent function restricted to any of the intervals $\left(-\frac{\pi}{2}, -\frac{\pi}{2}\right)$, $\left(-\frac{\pi}{2}, \frac{\pi}{2}\right)$, $\left(\frac{\pi}{2}, \frac{\pi}{2}\right)$ etc., is bijective and its range is \mathbf{R} . Thus \tan^{-1} can be defined as a function whose domain is \mathbf{R} and range could be any of the intervals $\left(-\frac{\pi}{2}, -\frac{\pi}{2}\right)$, $\left(-\frac{\pi}{2}, \frac{\pi}{2}\right)$, $\left(\frac{\pi}{2}, \frac{\pi}{2}\right)$ and so on. These intervals give different branches of the function \tan^{-1} . The branch with range $\left(-\frac{\pi}{2}, \frac{\pi}{2}\right)$ is called the *principal value branch* of the function \tan^{-1} .

e thus have

$$\tan^{-1} : \mathbf{R} \rightarrow \left(-\frac{\pi}{2}, \frac{\pi}{2}\right)$$

The graphs of the function $y = \tan x$ and $y = \tan^{-1}x$ are given in ig 2. (i), (ii).

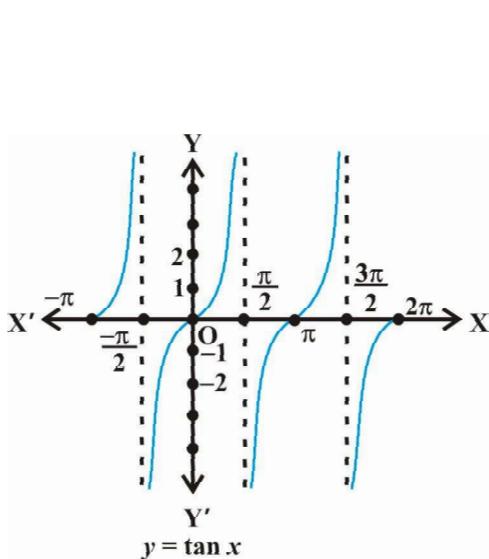


Fig 2.5 (i)

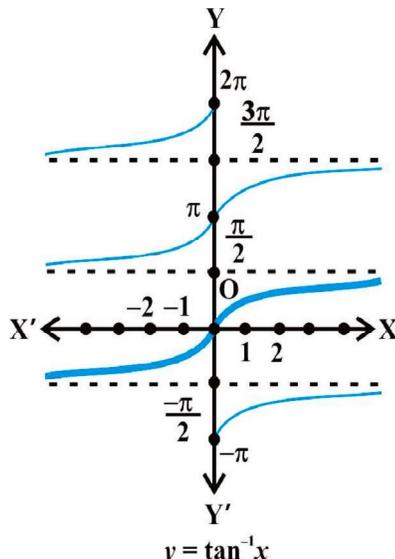


Fig 2.5 (ii)

e know that domain of the cot function (cotangent function) is the set $\{x : x \in \mathbf{R} \text{ and } x \neq n\pi, n \in \mathbf{Z}\}$ and range is \mathbf{R} . It means that cotangent function is not defined for integral multiples of π . If we restrict the domain of cotangent function to $(-\pi, \pi)$, then it is bijective with and its range as \mathbf{R} . In fact, cotangent function restricted to any of the intervals $(-\pi, \pi), (\pi, 2\pi)$ etc., is bijective and its range is \mathbf{R} . Thus \cot^{-1} can be defined as a function whose domain is the \mathbf{R} and range as any of the

intervals $(-\pi, 0)$, $(0, \pi)$, $(\pi, 2\pi)$ etc. These intervals give different branches of the function \cot^{-1} . The function with range $(0, \pi)$ is called the *principal value branch* of the function \cot^{-1} . We thus have

$$\cot^{-1} : \mathbf{R} \rightarrow (0, \pi)$$

The graphs of $y = \cot x$ and $y = \cot^{-1}x$ are given in fig 2. (i), (ii).

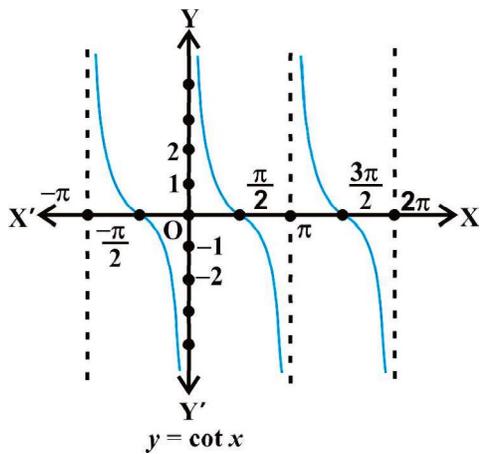


Fig 2.6 (i)

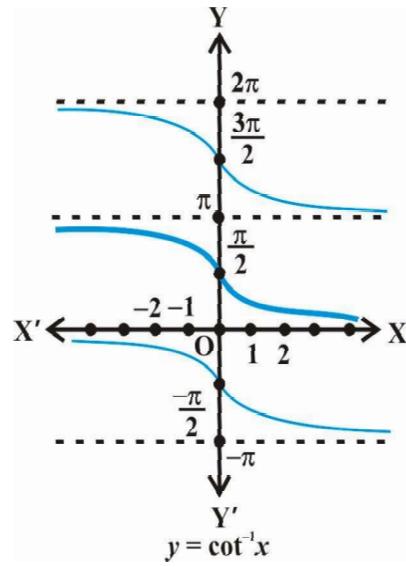


Fig 2.6 (ii)

The following table gives the inverse trigonometric function (principal value branches) along with their domains and ranges.

\sin^{-1}	:	$[-1, 1]$	\rightarrow	$\left[-\frac{\pi}{2}, \frac{\pi}{2}\right]$
\cos^{-1}	:	$[-1, 1]$	\rightarrow	$[0, \pi]$
$\operatorname{cosec}^{-1}$:	$\mathbf{R} - (-1, 1)$	\rightarrow	$\left[-\frac{\pi}{2}, \frac{\pi}{2}\right] - \{0\}$
\sec^{-1}	:	$\mathbf{R} - (-1, 1)$	\rightarrow	$[0, \pi] - \left\{\frac{\pi}{2}\right\}$
\tan^{-1}	:	\mathbf{R}	\rightarrow	$\left(-\frac{\pi}{2}, \frac{\pi}{2}\right)$
\cot^{-1}	:	\mathbf{R}	\rightarrow	$(0, \pi)$

Note

- $\sin^{-1}x$ should not be confused with $(\sin x)^{-1}$. In fact $(\sin x)^{-1} = \frac{1}{\sin x}$ and similarly for other trigonometric functions.
- Whenever no branch of an inverse trigonometric function is mentioned, we mean the principal value branch of that function.
- The value of an inverse trigonometric function which lies in the range of principal branch is called the *principal value* of that inverse trigonometric function.

we now consider some examples:

Example 1 Find the principal value of $\sin^{-1}\left(\frac{1}{\sqrt{2}}\right)$.

Solution Let $\sin^{-1}\left(\frac{1}{\sqrt{2}}\right) = y$. Then, $\sin y = \frac{1}{\sqrt{2}}$.

We know that the range of the principal value branch of \sin^{-1} is $\left(-\frac{\pi}{2}, \frac{\pi}{2}\right)$ and $\sin\left(\frac{\pi}{4}\right) = \frac{1}{\sqrt{2}}$. Therefore, principal value of $\sin^{-1}\left(\frac{1}{\sqrt{2}}\right)$ is $\frac{\pi}{4}$.

Example 2 Find the principal value of $\cot^{-1}\left(\frac{-1}{\sqrt{3}}\right)$.

Solution Let $\cot^{-1}\left(\frac{-1}{\sqrt{3}}\right) = y$. Then,

$$\cot y = \frac{-1}{\sqrt{3}} = -\cot\left(\frac{\pi}{3}\right) = \cot\left(\pi - \frac{\pi}{3}\right) = \cot\left(\frac{2\pi}{3}\right)$$

We know that the range of principal value branch of \cot^{-1} is $(0, \pi)$ and $\cot\left(\frac{2\pi}{3}\right) = \frac{-1}{\sqrt{3}}$. Hence, principal value of $\cot^{-1}\left(\frac{-1}{\sqrt{3}}\right)$ is $\frac{2\pi}{3}$.

EXERCISE 2.1

Find the principal values of the following:

- $\sin^{-1}\left(-\frac{1}{2}\right)$
- $\cos^{-1}\left(\frac{\sqrt{3}}{2}\right)$
- $\operatorname{cosec}^{-1}(2)$
- $\tan^{-1}(-\sqrt{3})$
- $\cos^{-1}\left(-\frac{1}{2}\right)$
- $\tan^{-1}(-1)$

$$7. \sec^{-1} \left(\frac{2}{\sqrt{e}} \right) \quad 8. \cot^{-1} (\sqrt{e}) \quad 9. \cos^{-1} \left(-\frac{1}{\sqrt{2}} \right)$$

$$10. \operatorname{cosec}^{-1} (-\sqrt{2})$$

find the values of the following:

$$11. \tan^{-1}(1) + \cos^{-1} \left(-\frac{1}{2} \right) + \sin^{-1} \left(-\frac{1}{2} \right) \quad 12. \cos^{-1} \left(\frac{1}{2} \right) + 2 \sin^{-1} \left(\frac{1}{2} \right)$$

13. If $\sin^{-1} x = y$, then

$$(A) \quad -\pi \leq y \leq \pi \quad (B) \quad -\frac{\pi}{2} \leq y \leq \frac{\pi}{2}$$

$$(C) \quad y \in \pi \quad (D) \quad -\frac{\pi}{2} < y < \frac{\pi}{2}$$

14. $\tan^{-1} \sqrt{\sec^{-1}(-\frac{1}{2})}$ is equal to

$$(A) \quad \pi \quad (B) \quad -\frac{\pi}{2} \quad (C) \quad \frac{\pi}{2} \quad (D) \quad \frac{2\pi}{3}$$

2.3 Properties of Inverse Trigonometric Functions

In this section, we shall prove some important properties of inverse trigonometric functions. It may be mentioned here that these results are valid within the principal value branches of the corresponding inverse trigonometric functions and wherever they are defined. Some results may not be valid for all values of the domains of inverse trigonometric functions. In fact, they will be valid only for some values of x for which inverse trigonometric functions are defined. We will not go into the details of these values of x in the domain as this discussion goes beyond the scope of this text book.

Let us recall that if $y = \sin^{-1}x$, then $x = \sin y$ and if $x = \sin y$, then $y = \sin^{-1}x$. This is equivalent to

$$\sin(\sin^{-1}x) = x, x \in [-1, 1] \text{ and } \sin^{-1}(\sin x) = x, x \in \left[-\frac{\pi}{2}, \frac{\pi}{2} \right]$$

The same is true for other five inverse trigonometric functions as well. We now prove some properties of inverse trigonometric functions.

$$1. \text{ (i) } \sin^{-1} \frac{1}{x} = \operatorname{cosec}^{-1} x, x \geq 1 \text{ or } x \leq -1$$

$$\text{ (ii) } \cos^{-1} \frac{1}{x} = \sec^{-1} x, x \geq 1 \text{ or } x \leq -1$$

$$\text{(iii) } \tan^{-1} \frac{1}{x} = \cot^{-1} x, x > 0$$

To prove the first result, we put $\operatorname{cosec}^{-1} x = y$, i.e., $x = \operatorname{cosec} y$

$$\text{Therefore } \frac{1}{x} = \sin y$$

$$\text{ence } \sin^{-1} \frac{1}{x} = y$$

$$\text{or } \sin^{-1} \frac{1}{x} = \operatorname{cosec}^{-1} x$$

imilarly, we can prove the other parts.

$$2. \text{ (i) } \sin^{-1} (-x) = -\sin^{-1} x, x \in [-1, 1]$$

$$\text{(ii) } \tan^{-1} (-x) = -\tan^{-1} x, x \in \mathbf{R}$$

$$\text{(iii) } \operatorname{cosec}^{-1} (-x) = -\operatorname{cosec}^{-1} x, |x| \geq 1$$

et $\sin^{-1}(-x) = y$, i.e., $-x = \sin y$ so that $x = -\sin y$, i.e., $x = \sin(-y)$.

$$\text{ence } \sin^{-1} x = -y = -\sin^{-1}(-x)$$

$$\text{Therefore } \sin^{-1}(-x) = -\sin^{-1} x$$

imilarly, we can prove the other parts.

$$3. \text{ (i) } \cos^{-1} (-x) = \pi - \cos^{-1} x, x \in [-1, 1]$$

$$\text{(ii) } \sec^{-1} (-x) = \pi - \sec^{-1} x, |x| \geq 1$$

$$\text{(iii) } \cot^{-1} (-x) = \pi - \cot^{-1} x, x \in \mathbf{R}$$

et $\cos^{-1}(-x) = y$ i.e., $-x = \cos y$ so that $x = -\cos y = \cos(\pi - y)$

$$\text{Therefore } \cos^{-1} x = \pi - y = \pi - \cos^{-1}(-x)$$

$$\text{ence } \cos^{-1}(-x) = \pi - \cos^{-1} x$$

imilarly, we can prove the other parts.

$$4. \text{ (i) } \sin^{-1} x + \cos^{-1} x = \frac{\pi}{2}, x \in [-1, 1]$$

$$\text{(ii) } \tan^{-1} x + \cot^{-1} x = \frac{\pi}{2}, x \in \mathbf{R}$$

$$\text{(iii) } \operatorname{cosec}^{-1} x + \sec^{-1} x = \frac{\pi}{2}, |x| \geq 1$$

$$\text{et } \sin^{-1} x = y. \text{ Then } x = \sin y = \cos\left(\frac{\pi}{2} - y\right)$$

$$\text{Therefore } \cos^{-1} x = \frac{\pi}{2} - y = \frac{\pi}{2} - \sin^{-1} x$$

$$\text{ence} \quad \sin^{-1} x + \cos^{-1} x = \frac{\pi}{2}$$

imilarly, we can prove the other parts.

$$5. \text{ (i) } \tan^{-1} x + \tan^{-1} y = \tan^{-1} \frac{x+y}{1-xy}, xy < 1$$

$$\text{(ii) } \tan^{-1} x - \tan^{-1} y = \tan^{-1} \frac{x-y}{1+xy}, xy > -1$$

et $\tan^{-1} x = \theta$ and $\tan^{-1} y = \phi$. Then $x = \tan \theta$, $y = \tan \phi$

$$\text{ow} \quad \tan(\theta + \phi) = \frac{\tan \theta + \tan \phi}{1 - \tan \theta \tan \phi} = \frac{x+y}{1-xy}$$

$$\text{This gives} \quad \theta + \phi = \tan^{-1} \frac{x+y}{1-xy}$$

$$\text{ence} \quad \tan^{-1} x + \tan^{-1} y = \tan^{-1} \frac{x+y}{1-xy}$$

In the above result, if we replace y by $-y$, we get the second result and by replacing y by x , we get the third result as given below.

$$6. \text{ (i) } 2\tan^{-1} x = \sin^{-1} \frac{2x}{1+x^2}, |x| \leq 1$$

$$\text{(ii) } 2\tan^{-1} x = \cos^{-1} \frac{1-x^2}{1+x^2}, x \geq 0$$

$$\text{(iii) } 2 \tan^{-1} x = \tan^{-1} \frac{2x}{1-x^2}, -1 < x < 1$$

et $\tan^{-1} x = y$, then $x = \tan y$. ow

$$\begin{aligned} \sin^{-1} \frac{2x}{1+x^2} &= \sin^{-1} \frac{2 \tan y}{1 + \tan^2 y} \\ &= \sin^{-1} (\sin 2y) = 2y = 2 \tan^{-1} x \end{aligned}$$

$$\text{Iso } \cos^{-1} \frac{1-x^2}{1+x^2} = \cos^{-1} \frac{1-\tan^2 y}{1+\tan^2 y} = \cos^{-1} (\cos 2y) = 2y = 2\tan^{-1} x$$

(iii) Can be worked out similarly.

e now consider some examples.

Example 3 how that

$$(i) \sin^{-1} (2x\sqrt{1-x^2}) = 2 \sin^{-1} x, \quad -\frac{1}{\sqrt{2}} \leq x \leq \frac{1}{\sqrt{2}}$$

$$(ii) \sin^{-1} (2x\sqrt{1-x^2}) = 2 \cos^{-1} x, \quad \frac{1}{\sqrt{2}} \leq x \leq 1$$

Solution

(i) et $x = \sin \theta$. Then $\sin^{-1} x = \theta$. e have

$$\begin{aligned} \sin^{-1} (2x\sqrt{1-x^2}) &= \sin^{-1} (2 \sin \theta \sqrt{1-\sin^2 \theta}) \\ &= \sin^{-1} (2 \sin \theta \cos \theta) = \sin^{-1} (\sin 2\theta) = 2\theta \\ &= 2 \sin^{-1} x \end{aligned}$$

(ii) Take $x = \cos \theta$, then proceeding as above, we get, $\sin^{-1} (2x\sqrt{1-x^2}) = 2 \cos^{-1} x$

Example 4 how that $\tan^{-1} \frac{1}{2} + \tan^{-1} \frac{2}{11} = \tan^{-1} \frac{1}{2}$

Solution By property (i), we have

$$\dots = \tan^{-1} \frac{1}{2} + \tan^{-1} \frac{2}{11} = \tan^{-1} \frac{\frac{1}{2} + \frac{2}{11}}{1 - \frac{1}{2} \times \frac{2}{11}} = \tan^{-1} \frac{1}{2} = \tan^{-1} \frac{1}{2} = \dots$$

Example 5 xpress $\tan^{-1} \left(\frac{\cos x}{1-\sin x} \right)$, $-\frac{\pi}{2} < x < \frac{\pi}{2}$ in the simplest form.

Solution e write

$$\tan^{-1} \left(\frac{\cos x}{1-\sin x} \right) = \tan^{-1} \left[\frac{\cos^2 \frac{x}{2} - \sin^2 \frac{x}{2}}{\cos^2 \frac{x}{2} + \sin^2 \frac{x}{2} - 2 \sin \frac{x}{2} \cos \frac{x}{2}} \right]$$

$$\begin{aligned}
&= \tan^{-1} \left[\frac{\left(\cos \frac{x}{2} + \sin \frac{x}{2} \right) \left(\cos \frac{x}{2} - \sin \frac{x}{2} \right)}{\left(\cos \frac{x}{2} - \sin \frac{x}{2} \right)^2} \right] \\
&= \tan^{-1} \left[\frac{\cos \frac{x}{2} + \sin \frac{x}{2}}{\cos \frac{x}{2} - \sin \frac{x}{2}} \right] = \tan^{-1} \left[\frac{1 + \tan \frac{x}{2}}{1 - \tan \frac{x}{2}} \right] \\
&= \tan^{-1} \left[\tan \left(\frac{\pi}{2} + \frac{x}{2} \right) \right] = \frac{\pi}{2} + \frac{x}{2}
\end{aligned}$$

Alternatively,

$$\begin{aligned}
\tan^{-1} \left(\frac{\cos x}{1 - \sin x} \right) &= \tan^{-1} \left[\frac{\sin \left(\frac{\pi}{2} - x \right)}{1 - \cos \left(\frac{\pi}{2} - x \right)} \right] = \tan^{-1} \left[\frac{\sin \left(\frac{\pi - 2x}{2} \right)}{1 - \cos \left(\frac{\pi - 2x}{2} \right)} \right] \\
&= \tan^{-1} \left[\frac{2 \sin \left(\frac{\pi - 2x}{2} \right) \cos \left(\frac{\pi - 2x}{2} \right)}{2 \sin^2 \left(\frac{\pi - 2x}{2} \right)} \right] \\
&= \tan^{-1} \left[\cot \left(\frac{\pi - 2x}{2} \right) \right] = \tan^{-1} \left[\tan \left(\frac{\pi}{2} - \frac{\pi - 2x}{2} \right) \right] \\
&= \tan^{-1} \left[\tan \left(\frac{\pi}{2} + \frac{x}{2} \right) \right] = \frac{\pi}{2} + \frac{x}{2}
\end{aligned}$$

Example 6 rite $\cot^{-1} \left(\frac{1}{\sqrt{x^2 - 1}} \right)$, $x > 1$ in the simplest form.

Solution et $x = \sec \theta$, then $\sqrt{x^2 - 1} = \sqrt{\sec^2 \theta - 1} = \tan \theta$

Therefore, $\cot^{-1} \frac{1}{\sqrt{x^2-1}} = \cot^{-1}(\cot \theta) = \theta = \sec^{-1} x$, which is the simplest form.

Example 7 Prove that $\tan^{-1} x + \tan^{-1} \frac{2x}{1-x^2} = \tan^{-1} \left(\frac{x-x}{1-x^2} \right)$, $x < \frac{1}{\sqrt{}}$

Solution Let $x = \tan \theta$. Then $\theta = \tan^{-1} x$. We have

$$\begin{aligned} \dots &= \tan^{-1} \left(\frac{\tan \theta - x}{1 - x^2} \right) = \tan^{-1} \left(\frac{\theta - \theta}{1 - \tan^2 \theta} \right) \\ &= \tan^{-1}(\tan \theta) = \theta = \tan^{-1} x = \tan^{-1} x + 2 \tan^{-1} x \\ &= \tan^{-1} x + \tan^{-1} \frac{2x}{1-x^2} = \dots \text{ (hy)} \end{aligned}$$

Example 8 Find the value of $\cos(\sec^{-1} x + \operatorname{cosec}^{-1} x)$, $|x| \geq 1$

Solution We have $\cos(\sec^{-1} x + \operatorname{cosec}^{-1} x) = \cos\left(\frac{\pi}{2}\right) =$

EXERCISE 2.2

Prove the following:

1. $\sin^{-1} x = \sin^{-1}(x - x)$, $x \in \left[-\frac{1}{2}, \frac{1}{2}\right]$
2. $\cos^{-1} x = \cos^{-1}(x - x)$, $x \in \left[\frac{1}{2}, 1\right]$
3. $\tan^{-1} \frac{2}{11} + \tan^{-1} \frac{1}{22} = \tan^{-1} \frac{1}{11}$
4. $2 \tan^{-1} \frac{1}{2} + \tan^{-1} \frac{1}{1} = \tan^{-1} \frac{1}{1}$

Write the following functions in the simplest form:

5. $\tan^{-1} \frac{\sqrt{1+x^2}-1}{x}$, $x \neq 0$
6. $\tan^{-1} \frac{1}{\sqrt{x^2-1}}$, $x > 1$
7. $\tan^{-1} \left(\frac{1-\cos x}{1+\cos x} \right)$, $x \in \pi$
8. $\tan^{-1} \left(\frac{\cos x - \sin x}{\cos x + \sin x} \right)$, $x \in \pi$

$$9. \tan^{-1} \frac{x}{\sqrt{a^2 - x^2}}, \quad x < a$$

$$10. \tan^{-1} \left(\frac{a^2 x - x}{a^2 - ax} \right), \quad a > 0, \quad \frac{-a}{\sqrt{a^2 - x^2}} < x < \frac{a}{\sqrt{a^2 - x^2}}$$

find the values of each of the following:

$$11. \tan^{-1} \left[2 \cos \left(2 \sin^{-1} \frac{1}{2} \right) \right] \qquad 12. \cot (\tan^{-1} a + \cot^{-1} a)$$

$$13. \tan \frac{1}{2} \left[\sin^{-1} \frac{2x}{1+x^2} + \cos^{-1} \frac{1-y^2}{1+y^2} \right], \quad x > 0, \quad y > 0 \text{ and } xy < 1$$

$$14. \text{ If } \sin \left(\sin^{-1} \frac{1}{2} + \cos^{-1} x \right) = 1, \text{ then find the value of } x$$

$$15. \text{ If } \tan^{-1} \frac{x-1}{x-2} + \tan^{-1} \frac{x+1}{x+2} = \frac{\pi}{4}, \text{ then find the value of } x$$

find the values of each of the expressions in exercises 16 to 21.

$$16. \sin^{-1} \left(\sin \frac{2\pi}{3} \right) \qquad 17. \tan^{-1} \left(\tan \frac{\pi}{4} \right)$$

$$18. \tan \left(\sin^{-1} \frac{1}{2} + \cot^{-1} 1 \right)$$

$$19. \cos^{-1} \left(\cos \frac{\pi}{3} \right) \text{ is equal to}$$

$$(A) \frac{\pi}{3} \qquad (B) \frac{\pi}{2} \qquad (C) \frac{\pi}{4} \qquad (D) \frac{\pi}{6}$$

$$20. \sin \left(\frac{\pi}{2} - \sin^{-1} \left(-\frac{1}{2} \right) \right) \text{ is equal to}$$

$$(A) \frac{1}{2} \qquad (B) \frac{1}{4} \qquad (C) \frac{1}{3} \qquad (D) 1$$

$$21. \tan^{-1} \sqrt{\cot \left(\sin^{-1} \frac{1}{\sqrt{2}} \right)} \text{ is equal to}$$

$$(A) \frac{\pi}{4} \qquad (B) \frac{\pi}{2} \qquad (C) 0 \qquad (D) 2\sqrt{2}$$

Miscellaneous Examples

Example 9 Find the value of $\sin^{-1}(\sin \frac{\pi}{2})$

Solution We know that $\sin^{-1}(\sin x) = x$. Therefore, $\sin^{-1}(\sin \frac{\pi}{2}) = \frac{\pi}{2}$

But $\frac{\pi}{2} \notin [-\frac{\pi}{2}, \frac{\pi}{2}]$, which is the principal branch of $\sin^{-1} x$

however $\sin(\frac{2\pi}{2}) = \sin(\pi - \frac{\pi}{2}) = \sin \frac{\pi}{2}$ and $\frac{2\pi}{2} \in [-\frac{\pi}{2}, \frac{\pi}{2}]$

Therefore $\sin^{-1}(\sin \frac{2\pi}{2}) = \frac{2\pi}{2} = \pi$

Example 10 Show that $\sin^{-1} \frac{1}{2} - \sin^{-1} \frac{1}{\sqrt{2}} = \cos^{-1} \frac{1}{2}$

Solution Let $\sin^{-1} \frac{1}{2} = x$ and $\sin^{-1} \frac{1}{\sqrt{2}} = y$

Therefore $\sin x = \frac{1}{2}$ and $\sin y = \frac{1}{\sqrt{2}}$

Now $\cos x = \sqrt{1 - \sin^2 x} = \sqrt{1 - \frac{1}{4}} = \frac{\sqrt{3}}{2}$ (by)

and $\cos y = \sqrt{1 - \sin^2 y} = \sqrt{1 - \frac{1}{2}} = \frac{1}{\sqrt{2}}$

We have $\cos(x - y) = \cos x \cos y + \sin x \sin y$

$$= \frac{\sqrt{3}}{2} \times \frac{1}{\sqrt{2}} + \frac{1}{2} \times \frac{1}{\sqrt{2}} = \frac{\sqrt{3} + 1}{2\sqrt{2}}$$

Therefore $x - y = \cos^{-1} \left(\frac{\sqrt{3} + 1}{2\sqrt{2}} \right)$

Hence $\sin^{-1} \frac{1}{2} - \sin^{-1} \frac{1}{\sqrt{2}} = \cos^{-1} \frac{\sqrt{3} + 1}{2\sqrt{2}}$

Example 11 show that $\sin^{-1} \frac{12}{11} + \cos^{-1} \frac{5}{11} + \tan^{-1} \frac{5}{12} = \pi$

Solution let $\sin^{-1} \frac{12}{11} = x$, $\cos^{-1} \frac{5}{11} = y$, $\tan^{-1} \frac{5}{12} = z$

Then $\sin x = \frac{12}{11}$, $\cos y = \frac{5}{11}$, $\tan z = \frac{5}{12}$

Therefore $\cos x = \frac{5}{11}$, $\sin y = \frac{10}{11}$, $\tan x = \frac{5}{12}$ and $\tan y = \frac{10}{5} = 2$

We have $\tan(x+y) = \frac{\tan x + \tan y}{1 - \tan x \tan y} = \frac{\frac{5}{12} + 2}{1 - \frac{5}{12} \times 2} = -\frac{17}{1}$

hence $\tan(x+y) = -\tan z$

i.e., $\tan(x+y) = \tan(-z)$ or $\tan(x+y) = \tan(\pi - z)$

Therefore $x+y = -z$ or $x+y = \pi - z$

since x, y and z are positive, $x+y = \pi - z$ (hy)

hence $x+y+z = \pi$ or $\sin^{-1} \frac{12}{11} + \cos^{-1} \frac{5}{11} + \tan^{-1} \frac{5}{12} = \pi$

Example 12 simplify $\tan^{-1} \left[\frac{a \cos x - b \sin x}{b \cos x + a \sin x} \right]$, if $\frac{a}{b} \tan x < -1$

Solution we have,

$$\begin{aligned} \tan^{-1} \left[\frac{a \cos x - b \sin x}{b \cos x + a \sin x} \right] &= \tan^{-1} \left[\frac{\frac{a \cos x - b \sin x}{b \cos x}}{\frac{b \cos x + a \sin x}{b \cos x}} \right] = \tan^{-1} \left[\frac{\frac{a}{b} - \tan x}{1 + \frac{a}{b} \tan x} \right] \\ &= \tan^{-1} \frac{a}{b} - \tan^{-1}(\tan x) = \tan^{-1} \frac{a}{b} - x \end{aligned}$$

Example 13 solve $\tan^{-1} 2x + \tan^{-1} x = \frac{\pi}{4}$

Solution we have $\tan^{-1} 2x + \tan^{-1} x = \frac{\pi}{4}$

or
$$\tan^{-1} \left(\frac{2x + x}{1 - 2x \times x} \right) = \frac{\pi}{4}$$

i.e.
$$\tan^{-1} \left(\frac{x}{1 - x^2} \right) = \frac{\pi}{4}$$

Therefore
$$\frac{x}{1 - x^2} = \tan \frac{\pi}{4} = 1$$

or
$$x^2 + x - 1 = 0 \text{ i.e., } (x - 1)(x + 1) = 0$$

which gives
$$x = 1 \text{ or } x = -1.$$

since $x = -1$ does not satisfy the equation, as the ... of the equation becomes negative, $x = 1$ is the only solution of the given equation.

Miscellaneous Exercise on Chapter 2

find the value of the following:

1. $\cos^{-1} \left(\cos \frac{\pi}{4} \right)$

2. $\tan^{-1} \left(\tan \frac{\pi}{4} \right)$

prove that

3. $2 \sin^{-1} \frac{2}{5} = \tan^{-1} \frac{4}{3}$

4. $\sin^{-1} \frac{1}{2} + \sin^{-1} \frac{1}{\sqrt{3}} = \tan^{-1} \frac{2 + \sqrt{3}}{1}$

5. $\cos^{-1} \frac{12}{13} + \cos^{-1} \frac{3}{5} = \cos^{-1} \frac{16}{65}$

6. $\cos^{-1} \frac{12}{13} + \sin^{-1} \frac{5}{13} = \sin^{-1} \frac{12}{13}$

7. $\tan^{-1} \frac{1}{11} = \sin^{-1} \frac{1}{\sqrt{102}} + \cos^{-1} \frac{1}{\sqrt{102}}$

8. $\tan^{-1} \frac{1}{2} + \tan^{-1} \frac{1}{3} + \tan^{-1} \frac{1}{4} + \tan^{-1} \frac{1}{5} = \frac{\pi}{2}$

rove that

$$9. \tan^{-1} \sqrt{x} = \frac{1}{2} \cos^{-1} \left(\frac{1-x}{1+x} \right), x \in [0, 1]$$

$$10. \cot^{-1} \left(\frac{\sqrt{1+\sin x} + \sqrt{1-\sin x}}{\sqrt{1+\sin x} - \sqrt{1-\sin x}} \right) = \frac{x}{2}, x \in \left(0, \frac{\pi}{2} \right)$$

$$11. \tan^{-1} \left(\frac{\sqrt{1+x} - \sqrt{1-x}}{\sqrt{1+x} + \sqrt{1-x}} \right) = \frac{\pi}{2} - \frac{1}{2} \cos^{-1} x, -\frac{1}{\sqrt{2}} \leq x \leq 1 \text{ [int: ut } x = \cos 2\theta]$$

$$12. \frac{1}{2} \cos^{-1} \left(\frac{2}{\sin^{-1} x} \right) = -\sin^{-1} \frac{\sqrt{1-x^2}}{x}$$

olve the following equations:

$$13. 2 \tan^{-1}(\cos x) = \tan^{-1}(2 \operatorname{cosec} x) \quad 14. \tan^{-1} \frac{1-x}{1+x} = \frac{1}{2} \tan^{-1} x, (x > 0)$$

$$15. \sin(\tan^{-1} x), x > 1 \text{ is equal to}$$

$$(A) \frac{x}{\sqrt{1-x^2}} \quad (B) \frac{1}{\sqrt{1-x^2}} \quad (C) \frac{1}{\sqrt{1+x^2}} \quad (D) \frac{x}{\sqrt{1+x^2}}$$

$$16. \sin^{-1}(1-x) - 2 \sin^{-1} x = \frac{\pi}{2}, \text{ then } x \text{ is equal to}$$

$$(A) \frac{1}{2}, \quad (B) 1, \frac{1}{2} \quad (C) 0 \quad (D) \frac{1}{2}$$

$$17. \tan^{-1} \left(\frac{x}{y} \right) - \tan^{-1} \frac{x-y}{x+y} \text{ is equal to}$$

$$(A) \frac{\pi}{2} \quad (B) \frac{\pi}{4} \quad (C) \frac{\pi}{6} \quad (D) \frac{-\pi}{4}$$

Summary

- ◆ The domains and ranges (principal value branches) of inverse trigonometric functions are given in the following table:

Functions	Domain	Range (Principal Value Branches)
$y = \sin^{-1} x$	$[-1, 1]$	$\left[-\frac{\pi}{2}, \frac{\pi}{2}\right]$
$y = \cos^{-1} x$	$[-1, 1]$	$[0, \pi]$
$y = \operatorname{cosec}^{-1} x$	$\mathbf{R} - (-1, 1)$	$\left[-\frac{\pi}{2}, \frac{\pi}{2}\right] - \{0\}$
$y = \sec^{-1} x$	$\mathbf{R} - (-1, 1)$	$[0, \pi] - \left\{\frac{\pi}{2}\right\}$
$y = \tan^{-1} x$	\mathbf{R}	$\left(-\frac{\pi}{2}, \frac{\pi}{2}\right)$
$y = \cot^{-1} x$	\mathbf{R}	$(0, \pi)$

- ◆ $\sin^{-1}x$ should not be confused with $(\sin x)^{-1}$. In fact $(\sin x)^{-1} = \frac{1}{\sin x}$ and similarly for other trigonometric functions.
- ◆ The value of an inverse trigonometric functions which lies in its principal value branch is called the *principal value* of that inverse trigonometric functions.

or suitable values of domain, we have

- | | |
|---|---|
| <ul style="list-style-type: none"> ◆ $y = \sin^{-1} x \Rightarrow x = \sin y$ ◆ $\sin(\sin^{-1} x) = x$ ◆ $\sin^{-1} \frac{1}{x} = \operatorname{cosec}^{-1} x$ ◆ $\cos^{-1} \frac{1}{x} = \sec^{-1} x$ ◆ $\tan^{-1} \frac{1}{x} = \cot^{-1} x$ | <ul style="list-style-type: none"> ◆ $x = \sin y \Rightarrow y = \sin^{-1} x$ ◆ $\sin^{-1}(\sin x) = x$ ◆ $\cos^{-1}(-x) = \pi - \cos^{-1} x$ ◆ $\cot^{-1}(-x) = \pi - \cot^{-1} x$ ◆ $\sec^{-1}(-x) = \pi - \sec^{-1} x$ |
|---|---|

$$\blacklozenge \sin^{-1}(-x) = -\sin^{-1} x$$

$$\blacklozenge \tan^{-1} x + \cot^{-1} x = \frac{\pi}{2}$$

$$\blacklozenge \sin^{-1} x + \cos^{-1} x = \frac{\pi}{2}$$

$$\blacklozenge \tan^{-1} x + \tan^{-1} y = \tan^{-1} \frac{x+y}{1-xy}$$

$$\blacklozenge \tan^{-1} x - \tan^{-1} y = \tan^{-1} \frac{x-y}{1+xy}$$

$$\blacklozenge 2\tan^{-1} x = \sin^{-1} \frac{2x}{1+x^2} = \cos^{-1} \frac{1-x^2}{1+x^2}$$

$$\blacklozenge \tan^{-1}(-x) = -\tan^{-1} x$$

$$\blacklozenge \operatorname{cosec}^{-1}(-x) = -\operatorname{cosec}^{-1} x$$

$$\blacklozenge \operatorname{cosec}^{-1} x + \sec^{-1} x = \frac{\pi}{2}$$

$$\blacklozenge 2\tan^{-1} x = \tan^{-1} \frac{2x}{1-x^2}$$

Historical Note

The study of trigonometry was first started in India. The ancient Indian Mathematicians, ryabhata (.), Brahmagupta (.), Bhaskara I (.) and Bhaskara II (111 ..) got important results of trigonometry. If this knowledge went from India to Arabia and then from there to Europe. The Greeks had also started the study of trigonometry but their approach was so clumsy that when the Indian approach became known, it was immediately adopted throughout the world.

In India, the predecessor of the modern trigonometric functions, known as the sine of an angle, and the introduction of the sine function represents one of the main contributions of the *siddhantas* (Sanskrit astronomical works) to mathematics.

Bhaskara I (about ..) gave formulae to find the values of sine functions for angles more than .. sixteenth century Malayalam work *Yuktibhasa* contains a proof for the expansion of $\sin(A+B)$. Exact expressions for sines or cosines of $1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36$, etc., were given by Bhaskara II.

The symbols $\sin^{-1} x$, $\cos^{-1} x$, etc., for arc $\sin x$, arc $\cos x$, etc., were suggested by the astronomer Johann Heinrich Lambert (1768-1840). The name of Thales (about B.C.) is invariably associated with height and distance problems. He is credited with the determination of the height of a great pyramid in Egypt by measuring shadows of the pyramid and an auxiliary staff (or gnomon) of known

height, and comparing the ratios:

$$\frac{h}{s} = \tan(\text{sun's altitude})$$

Thales is also said to have calculated the distance of a ship at sea through the proportionality of sides of similar triangles. Problems on height and distance using the similarity property are also found in ancient Indian works.



MATRICES

❖ *The essence of Mathematics lies in its freedom.* — CANTOR ❖

3.1 Introduction

The knowledge of matrices is necessary in various branches of mathematics. Matrices are one of the most powerful tools in mathematics. This mathematical tool simplifies our work to a great extent when compared with other straight forward methods. The evolution of concept of matrices is the result of an attempt to obtain compact and simple methods of solving system of linear equations. Matrices are not only used as a representation of the coefficients in system of linear equations, but utility of matrices far exceeds that use. Matrix notation and operations are used in electronic spreadsheet programs for personal computer, which in turn is used in different areas of business and science like budgeting, sales projection, cost estimation, analysing the results of an experiment etc. Also, many physical operations such as magnification, rotation and reflection through a plane can be represented mathematically by matrices. Matrices are also used in cryptography. This mathematical tool is not only used in certain branches of sciences, but also in genetics, economics, sociology, modern psychology and industrial management.

In this chapter, we shall find it interesting to become acquainted with the fundamentals of matrix and matrix algebra.

3.2 Matrix

Suppose we wish to express the information that Radha has 15 notebooks. We may express it as [15] with the understanding that the number inside [] is the number of notebooks that Radha has. Now, if we have to express that Radha has 15 notebooks and 6 pens. We may express it as [15 6] with the understanding that first number inside [] is the number of notebooks while the other one is the number of pens possessed by Radha. Let us now suppose that we wish to express the information of possession

of notebooks and pens by Radha and her two friends Fauzia and Simran which is as follows

Radha	has	15	notebooks	and	6 pens,
Fauzia	has	10	notebooks	and	2 pens,
Simran	has	13	notebooks	and	5 pens.

Now this could be arranged in the tabular form as follows

	Notebooks	Pens
Radha	15	6
Fauzia	10	2
Simran	13	5

and this can be expressed as

$$\begin{array}{cc}
 \left[\begin{array}{cc} 15 & 6 \\ 10 & 2 \\ 13 & 5 \end{array} \right] & \begin{array}{l} \leftarrow \text{First row} \\ \leftarrow \text{Second row} \\ \leftarrow \text{Third row} \end{array} \\
 \begin{array}{c} \uparrow \\ \text{First} \\ \text{Column} \end{array} & \begin{array}{c} \uparrow \\ \text{Second} \\ \text{Column} \end{array}
 \end{array}$$

or

	Radha	Fauzia	Simran
Notebooks	15	10	13
Pens	6	2	5

which can be expressed as

$$\begin{array}{ccc}
 \left[\begin{array}{ccc} 15 & 10 & 13 \\ 6 & 2 & 5 \end{array} \right] & \begin{array}{l} \leftarrow \text{First row} \\ \leftarrow \text{Second row} \end{array} \\
 \begin{array}{c} \uparrow \\ \text{First} \\ \text{Column} \end{array} & \begin{array}{c} \uparrow \\ \text{Second} \\ \text{Column} \end{array} & \begin{array}{c} \uparrow \\ \text{Third} \\ \text{Column} \end{array}
 \end{array}$$

In the first arrangement the entries in the first column represent the number of note books possessed by Radha, Fauzia and Simran, respectively and the entries in the second column represent the number of pens possessed by Radha, Fauzia and Simran,

respectively. Similarly, in the second arrangement, the entries in the first row represent the number of notebooks possessed by Radha, Anika and Simran, respectively. The entries in the second row represent the number of pens possessed by Radha, Anika and Simran, respectively. An arrangement or display of the above kind is called a *matrix*. Formally, we define matrix as

Definition 1 A *matrix* is an ordered rectangular array of numbers or functions. The numbers or functions are called the elements or the entries of the matrix.

We denote matrices by capital letters. The following are some examples of matrices

$$A = \begin{bmatrix} 1 & 5 \\ 2 & \sqrt{5} \\ 3 & 6 \end{bmatrix}, B = \begin{bmatrix} i & -\frac{1}{2} \\ 5 & 1 \\ \sqrt{2} & 5 & \frac{5}{2} \end{bmatrix}, C = \begin{bmatrix} 1+x & x & 1 \\ \cos x & \sin x & \tan x \end{bmatrix}$$

In the above examples, the horizontal lines of elements are said to constitute, **rows** of the matrix and the vertical lines of elements are said to constitute, **columns** of the matrix. Thus A has 3 rows and 2 columns, B has 3 rows and 3 columns while C has 2 rows and 3 columns.

3.2.1 Order of a matrix

A matrix having m rows and n columns is called a matrix of *order* $m \times n$ or simply $m \times n$ matrix (read as an m by n matrix). So referring to the above examples of matrices, we have A as 3×2 matrix, B as 3×3 matrix and C as 2×3 matrix. We observe that A has $3 \times 2 = 6$ elements, B and C have 9 and 6 elements, respectively.

In general, an $m \times n$ matrix has the following rectangular array

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} & \dots & a_{1j} & \dots & a_{1n} \\ a_{21} & a_{22} & a_{23} & \dots & a_{2j} & \dots & a_{2n} \\ \vdots & \vdots & \vdots & \dots & \vdots & \dots & \vdots \\ a_{i1} & a_{i2} & a_{i3} & \dots & a_{ij} & \dots & a_{in} \\ \vdots & \vdots & \vdots & \dots & \vdots & \dots & \vdots \\ a_{m1} & a_{m2} & a_{m3} & \dots & a_{mj} & \dots & a_{mn} \end{bmatrix}_{m \times n}$$

or $A = [a_{ij}]_{m \times n}$, $1 \leq i \leq m$, $1 \leq j \leq n$ $i, j \in \mathbb{N}$

Thus the i^{th} row consists of the elements $a_{i1}, a_{i2}, a_{i3}, \dots, a_{in}$, while the j^{th} column consists of the elements $a_{1j}, a_{2j}, a_{3j}, \dots, a_{mj}$,

In general a_{ij} is an element lying in the i^{th} row and j^{th} column. We can also call it as the $(i, j)^{\text{th}}$ element of A. The number of elements in an $m \times n$ matrix will be equal to mn .

Note In this chapter

1. We shall follow the notation, namely $A = [a_{ij}]_{m \times n}$ to indicate that A is a matrix of order $m \times n$.
- We shall consider only those matrices whose elements are real numbers or functions taking real values.

We can also represent any point (x, y) in a plane by a matrix [column or row] as

$\begin{bmatrix} x \\ y \end{bmatrix}$ [or $[x, y]$] [or example point $(1, 1)$] as a matrix representation may be given as

$$\begin{bmatrix} 1 \\ 1 \end{bmatrix} \text{ or } [1 \ 1].$$

□bserve that in this way we can also express the vertices of a closed rectilinear figure in the form of a matrix. □or example, consider a quadrilateral ABCD with vertices $A(1, 1), B(1, 3), C(3, 3), D(3, 1)$

Now, quadrilateral ABCD in the matrix form, can be represented as

$$A = \begin{bmatrix} 1 & 1 & 3 & 3 \\ 1 & 3 & 3 & 1 \end{bmatrix}_{2 \times 4} \text{ or } A = \begin{bmatrix} 1 & 1 \\ 1 & 3 \\ 3 & 3 \\ -1 & 1 \end{bmatrix}_{4 \times 2}$$

Thus, matrices can be used as representation of vertices of geometrical figures in a plane.

Now, let us consider some examples.

Example 1 Consider the following information regarding the number of men and women workers in three factories I, II and III

	Men workers	Women workers
I	10	5
II	5	1
III	10	6

Represent the above information in the form of a 3×2 matrix. What does the entry in the third row and second column represent?

Solution The information is represented in the form of a 3×2 matrix as follows

$$A = \begin{bmatrix} 1 & 5 \\ 5 & 1 \\ 2 & 6 \end{bmatrix}$$

The entry in the third row and second column represents the number of women workers in factory III.

Example 2 If a matrix has 12 elements, what are the possible orders it can have

Solution We know that if a matrix is of order $m \times n$, it has mn elements. Thus, to find all possible orders of a matrix with 12 elements, we will find all ordered pairs of natural numbers, whose product is 12

Thus, all possible ordered pairs are $(1, 12), (2, 6), (3, 4), (4, 3), (6, 2), (12, 1)$

Hence, possible orders are $1 \times 12, 2 \times 6, 3 \times 4, 4 \times 3, 6 \times 2, 12 \times 1$

Example 3 Construct a 3×3 matrix whose elements are given by $a_{ij} = \frac{1}{i-j}$

Solution In general a 3×3 matrix is given by $A = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}$.

Now $a_{ij} = \frac{1}{i-j}, i = 1, 2, 3$ and $j = 1, 2, 3$

Therefore $a_{11} = \frac{1}{1-1} = \frac{1}{0} = 1$ $a_{12} = \frac{1}{1-2} = \frac{1}{-1} = -1$

$a_{21} = \frac{1}{2-1} = \frac{1}{1} = 1$ $a_{22} = \frac{1}{2-2} = \frac{1}{0} = 1$

$a_{31} = \frac{1}{3-1} = \frac{1}{2} = \frac{1}{2}$ $a_{32} = \frac{1}{3-2} = \frac{1}{1} = 1$

Hence the required matrix is given by $A = \begin{bmatrix} 1 & -1 & \frac{1}{2} \\ 1 & 1 & \frac{1}{2} \\ \frac{1}{2} & 1 & 1 \end{bmatrix}$.

3.3 Types of Matrices

In this section, we shall discuss different types of matrices.

i) Column matrix

A matrix is said to be a *column matrix* if it has only one column.

For example, $A = \begin{bmatrix} 2 \\ \sqrt{3} \\ -1 \\ 1 \end{bmatrix}$ is a column matrix of order 4×1 .

In general, $A = [a_{ij}]_{m \times 1}$ is a column matrix of order $m \times 1$.

ii) Row matrix

A matrix is said to be a *row matrix* if it has only one row.

For example, $B = \begin{bmatrix} -\frac{1}{2} & \sqrt{5} & 3 & 4 \end{bmatrix}_{1 \times 4}$ is a row matrix.

In general, $B = [b_{ij}]_{1 \times n}$ is a row matrix of order $1 \times n$.

iii) Square matrix

A matrix in which the number of rows are equal to the number of columns, is said to be a *square matrix*. Thus an $m \times n$ matrix is said to be a square matrix if $m = n$ and is known as a square matrix of order n .

For example $A = \begin{bmatrix} 2 & -1 & 3 \\ 4 & \sqrt{2} & 1 \\ 5 & 6 & -1 \end{bmatrix}$ is a square matrix of order 3.

In general, $A = [a_{ij}]_{m \times m}$ is a square matrix of order m .

Note If $A = [a_{ij}]$ is a square matrix of order n , then elements $a_{11}, a_{22}, \dots, a_{nn}$ are said to constitute the *diagonal*, of the matrix A . Thus, if $A = \begin{bmatrix} 1 & -2 & 1 \\ 3 & 4 & -1 \\ 5 & 6 & 7 \end{bmatrix}$. Then the elements of the diagonal of A are 1, 4, 7.

iv □ **Diagonal matrix**

A square matrix $[b_{ij}]_{m \times m}$ is said to be a *diagonal matrix* if all its non diagonal elements are zero, that is a matrix $[b_{ij}]_{m \times m}$ is said to be a diagonal matrix if $b_{ij} = 0$, when $i \neq j$.

For example, $A = \begin{bmatrix} -1 & 0 \\ 0 & 0 \end{bmatrix}$, $C = \begin{bmatrix} -1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$, are diagonal matrices

of order 1, 2, 3 respectively.

v □ **Scalar matrix**

A diagonal matrix is said to be a *scalar matrix* if its diagonal elements are equal, that is, a square matrix $[b_{ij}]_{n \times n}$ is said to be a scalar matrix if

$$\begin{aligned} b_{ij} &= 0 && \text{when } i \neq j \\ b_{ij} &= k, && \text{when } i = j, \text{ for some constant } k. \end{aligned}$$

For example

$$A = \begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix}, \quad C = \begin{bmatrix} \sqrt{0} & 0 & 0 \\ 0 & \sqrt{0} & 0 \\ 0 & 0 & \sqrt{0} \end{bmatrix}$$

are scalar matrices of order 1, 2 and 3 respectively.

vi □ **Identity matrix**

A square matrix in which elements in the diagonal are all 1 and rest are all zero is called an *identity matrix*. In other words, the square matrix $A = [a_{ij}]_{n \times n}$ is an

identity matrix, if $a_{ij} = \begin{cases} 1 & \text{if } i = j \\ 0 & \text{if } i \neq j \end{cases}$.

We denote the identity matrix of order n by I_n . When order is clear from the context, we simply write it as I .

For example $[1]$, $\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$, $\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$ are identity matrices of order 1, 2 and 3

respectively.

Observe that a scalar matrix is an identity matrix when $k = 1$. But every identity matrix is clearly a scalar matrix.

vii Zero matrix

A matrix is said to be *zero matrix* or *null matrix* if all its elements are zero.

For example, $\begin{bmatrix} 0 \\ 0 \end{bmatrix}$, $\begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$, $\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$, $\begin{bmatrix} 0 & 0 \end{bmatrix}$ are all zero matrices. We denote zero matrix by O . Its order will be clear from the context.

3.3.1 Equality of matrices

Definition 2 Two matrices $A = [a_{ij}]$ and $B = [b_{ij}]$ are said to be equal if

- (i) they are of the same order
- (ii) each element of A is equal to the corresponding element of B , that is $a_{ij} = b_{ij}$ for all i and j .

For example, $\begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}$ and $\begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}$ are equal matrices but $\begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}$ and $\begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}$ are not equal matrices. Symbolically, if two matrices A and B are equal, we write $A = B$.

If $\begin{bmatrix} x & y \\ z & a \\ b & c \end{bmatrix} = \begin{bmatrix} -1.5 & 0 \\ 0 & \sqrt{6} \\ 0 & 0 \end{bmatrix}$, then $x = -1.5, y = 0, z = 0, a = \sqrt{6}, b = 0, c = 0$

Example 4 If $\begin{bmatrix} x+1 & z+1 & y-1 \\ -6 & a-1 & 0 \\ b-1 & -1 & 0 \end{bmatrix} = \begin{bmatrix} 0 & 6 & y-1 \\ -6 & -1 & c+1 \\ b+1 & -1 & 0 \end{bmatrix}$

Find the values of a, b, c, x, y and z .

Solution As the given matrices are equal, therefore, their corresponding elements must be equal. Comparing the corresponding elements, we get

$$\begin{aligned} x+1 &= 0 & z+1 &= 6 & y-1 &= y-1 \\ a-1 &= -1 & 0 &= -1 & 0 &= c+1 \\ b-1 &= b+1 & -1 &= -1 & 0 &= 0 \end{aligned}$$

Simplifying, we get

$$a = 0, b = 0, c = 1, x = -1, y = 5, z = 5$$

Example 5 Find the values of a, b, c , and d from the following equation

$$\begin{bmatrix} a+b & a-b \\ 5c-d & c+d \end{bmatrix} = \begin{bmatrix} 0 & -1 \\ 11 & 0 \end{bmatrix}$$

Solution By equality of two matrices, equating the corresponding elements, we get

$$\begin{aligned} a + b &= 5c + d = 11 \\ a + b &= c + d \end{aligned}$$

Solving these equations, we get

$$a = 1, b = 1, c = 1 \text{ and } d = 1$$

EXERCISE 3.1

1. In the matrix $A = \begin{bmatrix} 5 & 1 & -1 \\ 5 & -1 & \frac{5}{1} \\ \sqrt{1} & 1 & -5 & 1 \end{bmatrix}$, write

- i The order of the matrix, ii The number of elements,
iii Write the elements $a_{11}, a_{12}, a_{21}, a_{22}, a_{31}$

2. If a matrix has 10 elements, what are the possible orders it can have? What, if it has 10 elements?
3. If a matrix has 10 elements, what are the possible orders it can have? What, if it has 5 elements?
4. Construct a 3 × 3 matrix, $A = [a_{ij}]$, whose elements are given by

$$\text{i } a_{ij} = \frac{i+j}{2} \quad \text{ii } a_{ij} = \frac{i}{j} \quad \text{iii } a_{ij} = \frac{i+j}{2}$$

5. Construct a 3 × 3 matrix, whose elements are given by

$$\text{i } a_{ij} = \frac{1}{2}(i+j) \quad \text{ii } a_{ij} = i - j$$

6. Find the values of x, y and z from the following equations

$$\text{i } \begin{bmatrix} 1 & 1 \\ x & 5 \end{bmatrix} = \begin{bmatrix} y & z \\ 1 & 5 \end{bmatrix} \quad \text{ii } \begin{bmatrix} x+y & 1 \\ 5+z & xy \end{bmatrix} = \begin{bmatrix} 6 & 1 \\ 5 & 1 \end{bmatrix} \quad \text{iii } \begin{bmatrix} x+y+z \\ x+z \\ y+z \end{bmatrix} = \begin{bmatrix} 1 \\ 5 \\ 1 \end{bmatrix}$$

7. Find the value of a, b, c and d from the equation

$$\begin{bmatrix} a-b & a+c \\ a-b & c+d \end{bmatrix} = \begin{bmatrix} -1 & 5 \\ 1 & 1 \end{bmatrix}$$

8. A $[a_{ij}]_{m \times n}$ is a square matrix, if
 A $m \times n$ $m \times m$ $m \times n$ None of these
9. Which of the given values of x and y make the following pair of matrices equal

$$\begin{bmatrix} x+5 & y-1 \\ y+1 & -x \end{bmatrix}, \begin{bmatrix} x & y-1 \\ x & x \end{bmatrix}$$
 A $x = \frac{-1}{2}, y = \frac{1}{2}$ Not possible to find
 C $y = \frac{-1}{2}, x = \frac{1}{2}$ $x = \frac{-1}{2}, y = \frac{1}{2}$
10. The number of all possible matrices of order 2×2 with each entry 0 or 1 is
 A 4 1 C 1 51

3.4 Operations on Matrices

In this section, we shall introduce certain operations on matrices, namely, addition of matrices, multiplication of a matrix by a scalar, difference and multiplication of matrices.

3.4.1 Addition of matrices

Suppose Atima has two factories at places A and B. Each factory produces sport shoes for boys and girls in three different price categories labelled 1, 2 and 3. The quantities produced by each factory are represented as matrices given below.

	Factory at A		Factory at B	
	Boys	Girls	Boys	Girls
1	$\begin{bmatrix} 80 & 60 \end{bmatrix}$	$\begin{bmatrix} 90 & 50 \end{bmatrix}$		
2	$\begin{bmatrix} 75 & 65 \end{bmatrix}$	$\begin{bmatrix} 70 & 55 \end{bmatrix}$		
3	$\begin{bmatrix} 90 & 85 \end{bmatrix}$	$\begin{bmatrix} 75 & 75 \end{bmatrix}$		

Suppose Atima wants to know the total production of sport shoes in each price category. Then the total production

In category 1 (for boys 80 + 90, for girls 60 + 50)

In category 2 (for boys 75 + 70, for girls 65 + 55)

In category 3 (for boys 90 + 75, for girls 85 + 75)

This can be represented in the matrix form as
$$\begin{bmatrix} 80+90 & 60+50 \\ 75+70 & 65+55 \\ 90+75 & 85+75 \end{bmatrix}.$$

This new matrix is the **sum** of the above two matrices. We observe that the sum of two matrices is a matrix obtained by adding the corresponding elements of the given matrices. Furthermore, the two matrices have to be of the same order.

Thus, if $A = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \end{bmatrix}$ is a 2×3 matrix and $B = \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \end{bmatrix}$ is another

2×3 matrix. Then, we define $A + B = \begin{bmatrix} a_{11} + b_{11} & a_{12} + b_{12} & a_{13} + b_{13} \\ a_{21} + b_{21} & a_{22} + b_{22} & a_{23} + b_{23} \end{bmatrix}$.

In general, if $A = [a_{ij}]$ and $B = [b_{ij}]$ are two matrices of the same order, say $m \times n$. Then, the sum of the two matrices A and B is *defined* as a matrix $C = [c_{ij}]_{m \times n}$, where $c_{ij} = a_{ij} + b_{ij}$, for all possible values of i and j .

Example 6 Given $A = \begin{bmatrix} \sqrt{2} & 1 & -1 \\ 2 & 3 & 4 \end{bmatrix}$ and $B = \begin{bmatrix} 3 & \sqrt{5} & 1 \\ -2 & 2 & \frac{1}{2} \end{bmatrix}$, find $A + B$

Since A, B are of the same order 2×3 . Therefore, addition of A and B is defined and is given by

$$A + B = \begin{bmatrix} \sqrt{2} + 3 & 1 + \sqrt{5} & -1 + 1 \\ 2 - 2 & 3 + 2 & 4 + \frac{1}{2} \end{bmatrix} = \begin{bmatrix} \sqrt{2} + 3 & 1 + \sqrt{5} & 0 \\ 0 & 6 & \frac{9}{2} \end{bmatrix}$$

Note

1. We emphasise that if A and B are not of the same order, then $A + B$ is not

defined. For example if $A = \begin{bmatrix} 2 & 3 \\ 1 & 4 \end{bmatrix}$, $B = \begin{bmatrix} 1 & 2 & 3 \\ 1 & 2 & 1 \end{bmatrix}$, then $A + B$ is not defined.

2. We may observe that addition of matrices is an example of binary operation on the set of matrices of the same order.

3.4.2 Multiplication of a matrix by a scalar

Now suppose that Fatima has doubled the production at a factory A in all categories (refer to Table 1)

Previously quantities (in standard units) produced by factory A were

$$\begin{matrix} & \text{Boys} & \text{Girls} \\ \begin{matrix} 1 \\ 2 \\ 3 \end{matrix} & \begin{bmatrix} 80 & 60 \\ 75 & 65 \\ 90 & 85 \end{bmatrix} \end{matrix}$$

Revised quantities produced by factory A are as given below

$$\begin{matrix} & \text{Boys} & \text{Girls} \\ \begin{matrix} 1 \\ 2 \\ 3 \end{matrix} & \begin{bmatrix} 120 & 90 \\ 112.5 & 97.5 \\ 135 & 127.5 \end{bmatrix} \end{matrix}$$

This can be represented in the matrix form as $\begin{bmatrix} 1.5 & 1.5 \\ 1.5 & 1.5 \\ 1.5 & 1.5 \end{bmatrix}$. We observe that

the new matrix is obtained by multiplying each element of the previous matrix by 1.5

In general, we may define *multiplication of a matrix* by a scalar as follows: if $A = [a_{ij}]_{m \times n}$ is a matrix and k is a scalar, then kA is another matrix which is obtained by multiplying each element of A by the scalar k .

In other words, $kA = [ka_{ij}]_{m \times n}$, that is, $(i, j)^{\text{th}}$ element of kA is ka_{ij} for all possible values of i and j .

For example, if $A = \begin{bmatrix} 1 & 1 & 1.5 \\ \sqrt{5} & 1 & -1 \\ 1 & 1 & 5 \end{bmatrix}$, then

$$1.5A = \begin{bmatrix} 1.5 & 1.5 & 2.25 \\ 1.5\sqrt{5} & 1.5 & -1.5 \\ 1.5 & 1.5 & 7.5 \end{bmatrix} = \begin{bmatrix} 1.5 & 1.5 & 2.25 \\ 2.25 & 1.5 & -1.5 \\ 1.5 & 1.5 & 7.5 \end{bmatrix}$$

Negative of a matrix The negative of a matrix is denoted by $-A$. We define $-A = (-1)A$.

□or example, let $A = \begin{bmatrix} \square & 1 \\ -5 & x \end{bmatrix}$, then $\square A$ is given by

$$\square A = \square \begin{bmatrix} \square & 1 \\ -5 & x \end{bmatrix} = \begin{bmatrix} -\square & -1 \\ 5 & -x \end{bmatrix}$$

Difference of matrices If $A = [a_{ij}]$, $B = [b_{ij}]$ are two matrices of the same order, say $m \times n$, then difference $A - B$ is defined as a matrix $C = [d_{ij}]$, where $d_{ij} = a_{ij} - b_{ij}$, for all value of i and j . In other words, $A - B = A + (-1)B$, that is sum of the matrix A and the matrix $(-1)B$.

Example 7 If $A = \begin{bmatrix} 1 & \square & \square \\ \square & \square & 1 \end{bmatrix}$ and $B = \begin{bmatrix} \square & -1 & \square \\ -1 & \square & \square \end{bmatrix}$, then find $A - B$.

Solution We have

$$\begin{aligned} A - B &= \begin{bmatrix} 1 & \square & \square \\ \square & \square & 1 \end{bmatrix} - \begin{bmatrix} \square & -1 & \square \\ -1 & \square & \square \end{bmatrix} \\ &= \begin{bmatrix} \square & \square & 6 \\ \square & 6 & \square \end{bmatrix} + \begin{bmatrix} -\square & 1 & -\square \\ 1 & \square & -\square \end{bmatrix} \\ &= \begin{bmatrix} \square - \square & \square + 1 & 6 - \square \\ \square + 1 & 6 + \square & \square - \square \end{bmatrix} = \begin{bmatrix} -1 & 5 & \square \\ 5 & 6 & \square \end{bmatrix} \end{aligned}$$

3.4.3 Properties of matrix addition

The addition of matrices satisfy the following properties □

i) **Commutative Law** If $A = [a_{ij}]$, $B = [b_{ij}]$ are matrices of the same order, say $m \times n$, then $A + B = B + A$.

Now
$$A + B = [a_{ij}] + [b_{ij}] = [a_{ij} + b_{ij}]$$

$$= [b_{ij} + a_{ij}] \text{ [addition of numbers is commutative]}$$

$$= [b_{ij}] + [a_{ij}] = B + A$$

ii) **Associative Law** □or any three matrices $A = [a_{ij}]$, $B = [b_{ij}]$, $C = [c_{ij}]$ of the same order, say $m \times n$, $(A + B) + C = A + (B + C)$

Now
$$(A + B) + C = [(a_{ij} + b_{ij}) + c_{ij}]$$

$$= [a_{ij} + b_{ij} + c_{ij}] = [a_{ij} + (b_{ij} + c_{ij})]$$

$$= [a_{ij} + b_{ij} + c_{ij}] \text{ [Why?]}$$

$$= [a_{ij}] + [b_{ij} + c_{ij}] = [a_{ij}] + [b_{ij}] + [c_{ij}] = A + B + C$$

- iii **Existence of additive identity** Let $A = [a_{ij}]$ be an $m \times n$ matrix and O be an $m \times n$ zero matrix, then $A + O = O + A = A$. In other words, O is the additive identity for matrix addition.
- iv **The existence of additive inverse** Let $A = [a_{ij}]_{m \times n}$ be any matrix, then we have another matrix as $-A = [-a_{ij}]_{m \times n}$ such that $A + (-A) = (-A) + A = O$. So $-A$ is the additive inverse of A or negative of A .

3.4.4 Properties of scalar multiplication of a matrix

If $A = [a_{ij}]$ and $B = [b_{ij}]$ be two matrices of the same order, say $m \times n$, and k and l are scalars, then

- i $k(A + B) = kA + kB$, ii $(k + l)A = kA + lA$
- iii $k(A + B) = k[A_{ij}] + k[B_{ij}]$

$$= k[a_{ij} + b_{ij}] = k[a_{ij}] + k[b_{ij}]$$

$$= [k a_{ij}] + [k b_{ij}] = kA + kB$$
- iii $(k + l)A = (k + l)[a_{ij}]$

$$= [(k + l)a_{ij}] = [k a_{ij}] + [l a_{ij}] = kA + lA$$

Example 8 If $A = \begin{bmatrix} 1 & -2 \\ 3 & 6 \end{bmatrix}$ and $B = \begin{bmatrix} 2 & -1 \\ 4 & 1 \end{bmatrix}$, then find the matrix X , such that

$$A + X = 5B.$$

Solution We have $A + X = 5B$

or $A + X = A + 5B - A$

or $A + X - A = 5B - A$ Matrix addition is commutative

or $X = 5B - A$ $-A$ is the additive inverse of A

or $X = 5B + (-A)$ O is the additive identity

or $X = \frac{1}{1} (5B - A)$

or
$$X = \frac{1}{1} \left(5 \begin{bmatrix} 2 & -1 \\ 4 & 1 \end{bmatrix} - \begin{bmatrix} 1 & -2 \\ 3 & 6 \end{bmatrix} \right) = \frac{1}{1} \left(\begin{bmatrix} 10 & -5 \\ 20 & 5 \end{bmatrix} + \begin{bmatrix} -1 & 2 \\ -3 & -6 \end{bmatrix} \right)$$

$$\frac{1}{\square} \begin{bmatrix} 1\square-16 & -1\square+\square \\ \square\square-\square & 1\square+\square \\ -\square5-6 & 5-1\square \end{bmatrix} = \frac{1}{\square} \begin{bmatrix} -6 & -1\square \\ 1\square & 1\square \\ -\square & -\square \end{bmatrix} = \begin{bmatrix} -\square & \frac{-1\square}{\square} \\ \square & \frac{1\square}{\square} \\ \frac{-\square}{\square} & \frac{-\square}{\square} \end{bmatrix}$$

Example 9 Find \square and \square , if $\square + \square = \begin{bmatrix} 5 & \square \\ \square & \square \end{bmatrix}$ and $\square - \square = \begin{bmatrix} \square & 6 \\ \square & -1 \end{bmatrix}$.

Solution We have $(\square + \square) + (\square - \square) = \begin{bmatrix} 5 & \square \\ \square & \square \end{bmatrix} + \begin{bmatrix} \square & 6 \\ \square & -1 \end{bmatrix}$.

or $\square \square \square \square \square \square \square \square \square \square \begin{bmatrix} \square & \square \\ \square & \square \end{bmatrix} \Rightarrow \square \square = \begin{bmatrix} \square & \square \\ \square & \square \end{bmatrix}$

or $\square \square \frac{1}{\square} \begin{bmatrix} \square & \square \\ \square & \square \end{bmatrix} = \begin{bmatrix} \square & \square \\ \square & \square \end{bmatrix}$

Also $\square \square \square \square \square \square \square \square \square \square \begin{bmatrix} 5 & \square \\ \square & \square \end{bmatrix} - \begin{bmatrix} \square & 6 \\ \square & -1 \end{bmatrix}$

or $\square \square \square \square \square \square \square \square \square \square \begin{bmatrix} 5-\square & \square-6 \\ \square & \square+1 \end{bmatrix} \Rightarrow \square \square = \begin{bmatrix} \square & -\square \\ \square & 1\square \end{bmatrix}$

or $\square \square \frac{1}{\square} \begin{bmatrix} \square & -\square \\ \square & 1\square \end{bmatrix} = \begin{bmatrix} 1 & -\square \\ \square & 5 \end{bmatrix}$

Example 10 Find the values of x and y from the following equation □

$$\square \begin{bmatrix} x & 5 \\ \square & y-\square \end{bmatrix} + \begin{bmatrix} \square & -\square \\ 1 & \square \end{bmatrix} = \begin{bmatrix} \square & 6 \\ 15 & 1\square \end{bmatrix}$$

Solution We have

$$\square \begin{bmatrix} x & 5 \\ \square & y-\square \end{bmatrix} + \begin{bmatrix} \square & -\square \\ 1 & \square \end{bmatrix} = \begin{bmatrix} \square & 6 \\ 15 & 1\square \end{bmatrix} \Rightarrow \begin{bmatrix} \square x & 1\square \\ 1\square & \square y-6 \end{bmatrix} + \begin{bmatrix} \square & -\square \\ 1 & \square \end{bmatrix} = \begin{bmatrix} \square & 6 \\ 15 & 1\square \end{bmatrix}$$

or
$$\begin{bmatrix} x + 1 & y - 6 \end{bmatrix} = \begin{bmatrix} 6 & 1 \end{bmatrix} \Rightarrow \begin{bmatrix} x + 6 & y - 1 \end{bmatrix} = \begin{bmatrix} 6 & 1 \end{bmatrix}$$

or $x = 0$ and $y = 7$ Why

or $x = 0$ and $y = 1$

or $x = \frac{0}{1}$ and $y = \frac{1}{1}$

i.e. $x = 0$ and $y = 1$

Example 11 Two farmers Ramkishan and Gurcharan Singh cultivate only three varieties of rice namely Basmati, Permal and Naura. The sale (in Rupees) of these varieties of rice by both the farmers in the month of September and October are given by the following matrices A and B.

September Sales (in Rupees)

$$A = \begin{bmatrix} \text{Basmati} & \text{Permal} & \text{Naura} \\ 10,000 & 20,000 & 30,000 \\ 50,000 & 30,000 & 10,000 \end{bmatrix} \begin{matrix} \text{Ramkishan} \\ \text{Gurcharan Singh} \end{matrix}$$

October Sales (in Rupees)

$$B = \begin{bmatrix} \text{Basmati} & \text{Permal} & \text{Naura} \\ 5000 & 10,000 & 6000 \\ 20,000 & 10,000 & 10,000 \end{bmatrix} \begin{matrix} \text{Ramkishan} \\ \text{Gurcharan Singh} \end{matrix}$$

- (i) Find the combined sales in September and October for each farmer in each variety.
- (ii) Find the decrease in sales from September to October.
- (iii) If both farmers receive 10% profit on gross sales, compute the profit for each farmer and for each variety sold in October.

Solution

- (i) Combined sales in September and October for each farmer in each variety is given by

$$A + B = \begin{bmatrix} \text{Basmati} & \text{Permal} & \text{Naura} \\ 15,000 & 30,000 & 36,000 \\ 70,000 & 40,000 & 20,000 \end{bmatrix} \begin{matrix} \text{Ramkishan} \\ \text{Gurcharan Singh} \end{matrix}$$

(ii) Change in sales from September to October is given by

$$A - B = \begin{matrix} & \begin{matrix} \text{Basmati} & \text{Permal} & \text{Naura} \end{matrix} \\ \begin{bmatrix} 5000 & 10,000 & 24,000 \\ 30,000 & 20,000 & 0 \end{bmatrix} & \begin{matrix} \text{Ramkishan} \\ \text{Gurcharan Singh} \end{matrix} \end{matrix}$$

(iii) 100 of 100 $\frac{1}{100} \times 1000000$

$$100 \times \begin{matrix} & \begin{matrix} \text{Basmati} & \text{Permal} & \text{Naura} \end{matrix} \\ \begin{bmatrix} 5000 & 10,000 & 6000 \\ 20,000 & 10,000 & 10,000 \end{bmatrix} & \begin{matrix} \text{Ramkishan} \\ \text{Gurcharan Singh} \end{matrix} \end{matrix}$$

$$100 \times \begin{matrix} & \begin{matrix} \text{Basmati} & \text{Permal} & \text{Naura} \end{matrix} \\ \begin{bmatrix} 100 & 200 & 120 \\ 400 & 200 & 200 \end{bmatrix} & \begin{matrix} \text{Ramkishan} \\ \text{Gurcharan Singh} \end{matrix} \end{matrix}$$

Thus, in October Ramkishan receives Rs 100, Rs 100 and Rs 100 as profit in the sale of each variety of rice, respectively, and Gurcharan Singh receives profit of Rs 100, Rs 100 and Rs 100 in the sale of each variety of rice, respectively.

3.4.5 Multiplication of matrices

Suppose Meera and Nadeem are two friends. Meera wants to buy 5 pens and 5 story books, while Nadeem needs 5 pens and 1 story book. They both go to a shop to enquire about the rates which are quoted as follows:

pen Rs 5 each, story book Rs 5 each.

How much money does each need to spend? Clearly, Meera needs Rs (5 × 5 + 5 × 5) that is Rs 50, while Nadeem needs (5 × 5 + 1 × 5) Rs, that is Rs 25. In terms of matrix representation, we can write the above information as follows:

Requirements Prices per piece (in Rupees) Money needed (in Rupees)

$$\begin{bmatrix} 5 & 5 \\ 5 & 1 \end{bmatrix} \begin{bmatrix} 5 \\ 5 \end{bmatrix} = \begin{bmatrix} 5 \times 5 + 5 \times 5 \\ 5 \times 5 + 1 \times 5 \end{bmatrix} = \begin{bmatrix} 50 \\ 25 \end{bmatrix}$$

Suppose that they enquire about the rates from another shop, quoted as follows:

pen Rs 4 each, story book Rs 4 each.

Now, the money required by Meera and Nadeem to make purchases will be respectively Rs (5 × 4 + 5 × 4) Rs 40 and Rs (5 × 4 + 1 × 4) Rs 24.

Again, the above information can be represented as follows□

Requirements Prices per piece (in Rupees) Money needed (in Rupees)

$$\begin{bmatrix} \square & 5 \\ \square & 1 \end{bmatrix} \begin{bmatrix} \square \\ \square \end{bmatrix} = \begin{bmatrix} \square \times \square + \square \times 5 \\ \square \times \square + 1 \times \square \end{bmatrix} = \begin{bmatrix} \square \square \\ \square \square \end{bmatrix}$$

Now, the information in both the cases can be combined and expressed in terms of matrices as follows□

Requirements Prices per piece (in Rupees) Money needed (in Rupees)

$$\begin{bmatrix} \square & 5 \\ \square & 1 \end{bmatrix} \begin{bmatrix} 5 & \square \\ 5 \square & \square \end{bmatrix} = \begin{bmatrix} 5 \times \square + 5 \times 5 \square & \square \times \square + \square \times 5 \\ \square \times 5 + 1 \times 5 \square & \square \times \square + 1 \times \square \end{bmatrix}$$

$$= \begin{bmatrix} 6 \square & \square \square \\ 5 \square & \square \square \end{bmatrix}$$

The above is an example of multiplication of matrices. We observe that, for multiplication of two matrices A and □, the number of columns in A should be equal to the number of rows in □. □urthermore for getting the elements of the product matrix, we take rows of A and columns of □, multiply them elementwise and take the sum. □ormally, we define multiplication of matrices as follows□

The *product* of two matrices A and □ is *defined* if the number of columns of A is equal to the number of rows of □. Let A □ [a_{ij}] be an m □ n matrix and □ □ [b_{jk}] be an n □ p matrix. Then the product of the matrices A and □ is the matrix C of order m □ p. To get the ith, kth element c_{ik} of the matrix C, we take the ith row of A and kth column of □, multiply them elementwise and take the sum of all these products. In other words, if A □ [a_{ij}]_{m □ n}, □ □ [b_{jk}]_{n □ p}, then the ith row of A is [a_{i1} a_{i□} ... a_{in}] and the kth column of

□ is $\begin{bmatrix} b_{1k} \\ b_{\square k} \\ \vdots \\ b_{nk} \end{bmatrix}$, then $c_{ik} = a_{i1} b_{1k} + a_{i\square} b_{\square k} + a_{i\square} b_{\square k} + \dots + a_{in} b_{nk} = \sum_{j=1}^n a_{ij} b_{jk}$.

The matrix C □ [c_{ik}]_{m □ p} is the product of A and □.

□or example, if $C = \begin{bmatrix} 1 & -1 & \square \\ \square & \square & \square \end{bmatrix}$ and $\square = \begin{bmatrix} \square & \square \\ -1 & 1 \\ 5 & -\square \end{bmatrix}$, then the product C□ is defined

and is given by $C = \begin{bmatrix} 1 & -1 & 2 \\ \square & \square & \square \\ 0 & 3 & 4 \end{bmatrix} \begin{bmatrix} \square & \square \\ -1 & 1 \\ 5 & -\square \end{bmatrix}$. This is a $\square \square \square$ matrix in which each

entry is the sum of the products across some row of C with the corresponding entries down some column of \square . These four computations are

$$\begin{array}{l} \text{Entry in} \\ \text{first row} \\ \text{first column} \end{array} \begin{bmatrix} 1 & -1 & 2 \\ \square & \square & \square \\ 0 & 3 & 4 \end{bmatrix} \begin{bmatrix} 2 & 7 \\ -1 & 1 \\ 5 & -4 \end{bmatrix} = \begin{bmatrix} (1)(2) + (-1)(-1) + (2)(5) & ? \\ ? & ? \end{bmatrix}$$

$$\begin{array}{l} \text{Entry in} \\ \text{first row} \\ \text{second column} \end{array} \begin{bmatrix} 1 & -1 & 2 \\ \square & \square & \square \\ 0 & 3 & 4 \end{bmatrix} \begin{bmatrix} 2 & 7 \\ -1 & 1 \\ 5 & -4 \end{bmatrix} = \begin{bmatrix} 13 & (1)(7) + (-1)(1) + 2(-4) \\ ? & ? \end{bmatrix}$$

$$\begin{array}{l} \text{Entry in} \\ \text{second row} \\ \text{first column} \end{array} \begin{bmatrix} 1 & -1 & 2 \\ \square & \square & \square \\ 0 & 3 & 4 \end{bmatrix} \begin{bmatrix} 2 & 7 \\ -1 & 1 \\ 5 & -4 \end{bmatrix} = \begin{bmatrix} 13 & -2 \\ 0(2) + 3(-1) + 4(5) & ? \end{bmatrix}$$

$$\begin{array}{l} \text{Entry in} \\ \text{second row} \\ \text{second column} \end{array} \begin{bmatrix} 1 & -1 & 2 \\ \square & \square & \square \\ 0 & 3 & 4 \end{bmatrix} \begin{bmatrix} 2 & 7 \\ -1 & 1 \\ 5 & -4 \end{bmatrix} = \begin{bmatrix} 13 & -2 \\ 17 & 0(7) + 3(1) + 4(-4) \end{bmatrix}$$

$$\text{Thus } C = \begin{bmatrix} 1 & -1 & 2 \\ 1 & -1 & 2 \\ 0 & 3 & 4 \end{bmatrix}$$

Example 12 Find $A \square$, if $A = \begin{bmatrix} 6 & \square \\ \square & \square \end{bmatrix}$ and $\square = \begin{bmatrix} \square & 6 & \square \\ \square & \square & \square \end{bmatrix}$.

Solution The matrix A has \square columns which is equal to the number of rows of \square . Hence $A \square$ is defined. Now

$$A \square = \begin{bmatrix} 6\square + \square & 6\square + \square & 6\square + \square \\ \square + \square & \square + \square & \square + \square \end{bmatrix}$$

$$\square \begin{bmatrix} 1 & 6 & \square & \square \\ \square & 1 & \square & \square \end{bmatrix} \square \begin{bmatrix} \square & 11 & \square \\ \square & \square & \square \end{bmatrix}$$

Remark If AB is defined, then BA need not be defined. In the above example, AB is defined but BA is not defined because B has 3 columns while A has only 2 rows and not 3 rows. If A, B are, respectively $m \times n, k \times l$ matrices, then both AB and BA are defined **if and only if** $n = k$ and $l = m$. In particular, if both A and B are square matrices of the same order, then both AB and BA are defined.

Non-commutativity of multiplication of matrices

Now, we shall see by an example that even if AB and BA are both defined, it is not necessary that $AB = BA$.

Example 13 If $A = \begin{bmatrix} 1 & -2 & 3 \\ -2 & 2 & 5 \end{bmatrix}$ and $B = \begin{bmatrix} 2 & 3 \\ 2 & 5 \\ 2 & 1 \end{bmatrix}$, then find AB, BA . Show that

$AB \neq BA$.

Solution Since A is a 2×3 matrix and B is 3×2 matrix. Hence AB and BA are both defined and are matrices of order 2×2 and 2×2 respectively. Note that

$$AB = \begin{bmatrix} 1 & -2 & 3 \\ -2 & 2 & 5 \end{bmatrix} \begin{bmatrix} 2 & 3 \\ 2 & 5 \\ 2 & 1 \end{bmatrix} = \begin{bmatrix} 2-4+6 & 3-10+3 \\ -4+4+10 & -6+10+5 \end{bmatrix} = \begin{bmatrix} 4 & -4 \\ 6 & 9 \end{bmatrix}$$

and $BA = \begin{bmatrix} 2 & 3 \\ 2 & 5 \\ 2 & 1 \end{bmatrix} \begin{bmatrix} 1 & -2 & 3 \\ -2 & 2 & 5 \end{bmatrix} = \begin{bmatrix} 2-6 & -4+6 & 6+15 \\ 2-10 & -4+10 & 10+15 \\ 2-2 & -4+2 & 6+5 \end{bmatrix} = \begin{bmatrix} -4 & 2 & 21 \\ -8 & 6 & 25 \\ 0 & -2 & 11 \end{bmatrix}$

Clearly $AB \neq BA$

In the above example both AB and BA are of different order and so $AB \neq BA$. But one may think that perhaps AB and BA could be the same if they were of the same order. But it is not so, here we give an example to show that even if AB and BA are of same order they may not be same.

Example 14 If $A = \begin{bmatrix} 1 & 2 \\ 2 & -1 \end{bmatrix}$ and $B = \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix}$, then $AB = \begin{bmatrix} 2 & 1 \\ -1 & 2 \end{bmatrix}$.

and $BA = \begin{bmatrix} 2 & -1 \\ 1 & 2 \end{bmatrix}$. Clearly $AB \neq BA$.

Thus matrix multiplication is not commutative.

Note This does not mean that $AB \neq BA$ for every pair of matrices A, B for which AB and BA are defined. For instance,

If $A = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}$, $B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$, then $AB = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$

Observe that multiplication of diagonal matrices of same order will be commutative.

Zero matrix as the product of two non zero matrices

We know that, for real numbers a, b if $ab = 0$, then either $a = 0$ or $b = 0$. This need not be true for matrices, we will observe this through an example.

Example 15 Find AB , if $A = \begin{bmatrix} 0 & -1 \\ 0 & 0 \end{bmatrix}$ and $B = \begin{bmatrix} 0 & 5 \\ 0 & 0 \end{bmatrix}$.

Solution We have $AB = \begin{bmatrix} 0 & -1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} 0 & 5 \\ 0 & 0 \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$.

Thus, if the product of two matrices is a zero matrix, it is not necessary that one of the matrices is a zero matrix.

3.4.6 Properties of multiplication of matrices

The multiplication of matrices possesses the following properties, which we state without proof.

1. **The associative law** For any three matrices A, B and C . We have $(A \cdot B) \cdot C = A \cdot (B \cdot C)$, whenever both sides of the equality are defined.
2. **The distributive law** For three matrices A, B and C .
 - i) $A \cdot (B + C) = A \cdot B + A \cdot C$
 - ii) $(A + B) \cdot C = A \cdot C + B \cdot C$, whenever both sides of equality are defined.
3. **The existence of multiplicative identity** For every square matrix A , there exist an identity matrix of same order such that $IA = AI = A$.

Now, we shall verify these properties by examples.

Example 16 If $A = \begin{bmatrix} 1 & 1 & -1 \\ 0 & 0 & 0 \\ 0 & -1 & 0 \end{bmatrix}$, $B = \begin{bmatrix} 1 & 0 \\ 0 & 0 \\ -1 & 0 \end{bmatrix}$ and $C = \begin{bmatrix} 1 & 0 & 0 & -1 \\ 0 & 0 & -1 & 1 \end{bmatrix}$, find

$A \cdot C, B \cdot C$ and show that $(A \cdot B) \cdot C = A \cdot (B \cdot C)$

Solution We have $A \square = \begin{bmatrix} 1 & 1 & -1 \\ \square & \square & \square \\ \square & -1 & \square \end{bmatrix} \begin{bmatrix} 1 & \square \\ \square & \square \\ -1 & \square \end{bmatrix} = \begin{bmatrix} 1+\square+\square & \square+\square-\square \\ \square+\square-\square & 6+\square+\square \\ \square+\square-\square & \square-\square+\square \end{bmatrix} = \begin{bmatrix} \square & 1 \\ -1 & 1 \\ 1 & 15 \end{bmatrix}$

$$\square A \square \square C \square = \begin{bmatrix} \square & 1 \\ -1 & 1 \\ 1 & 15 \end{bmatrix} \begin{bmatrix} 1 & \square & \square & -\square \\ \square & \square & -\square & 1 \end{bmatrix} = \begin{bmatrix} \square+\square & \square+\square & 6-\square & -\square+1 \\ -1+\square & -\square+\square & -\square-\square & \square+1 \\ 1+\square & \square+\square & \square-\square & -\square+15 \end{bmatrix}$$

$$\square \begin{bmatrix} \square & \square & \square & -\square \\ \square & 5 & -\square & -\square \\ \square & 1 & \square & -\square \end{bmatrix}$$

Now $\square C \square = \begin{bmatrix} 1 & \square \\ \square & \square \\ -1 & \square \end{bmatrix} \begin{bmatrix} 1 & \square & \square & -\square \\ \square & \square & -\square & 1 \end{bmatrix} = \begin{bmatrix} 1+\square & \square+\square & \square-\square & -\square+\square \\ \square+\square & \square+\square & \square-\square & \square+\square \\ -1+\square & -\square+\square & -\square-\square & \square+\square \end{bmatrix}$

$$\square \begin{bmatrix} \square & \square & -\square & -1 \\ \square & \square & -\square & \square \\ \square & -\square & -11 & \square \end{bmatrix}$$

Therefore $A \square \square C \square \square = \begin{bmatrix} 1 & 1 & -1 \\ \square & \square & \square \\ \square & -1 & \square \end{bmatrix} \begin{bmatrix} \square & \square & -\square & -1 \\ \square & \square & -\square & \square \\ \square & -\square & -11 & \square \end{bmatrix}$

$$\square \begin{bmatrix} \square+\square-\square & \square+\square+\square & -\square-\square+11 & -1+\square-\square \\ 1+\square+\square & \square+\square-6 & -6+\square-\square & -\square+\square+\square \\ \square-\square+1 & 6+\square-\square & -\square+\square-\square & -\square-\square+16 \end{bmatrix}$$

$$\square \begin{bmatrix} \square & \square & \square & -\square \\ \square & 5 & -\square & -\square \\ \square & 1 & \square & -\square \end{bmatrix}. \text{ Clearly, } \square A \square \square C \square \square A \square \square C \square$$

Example 17 If $A = \begin{bmatrix} 1 & 6 & 1 \\ -6 & 1 & 1 \\ 1 & -1 & 1 \end{bmatrix}$, $B = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}$, $C = \begin{bmatrix} 1 \\ -1 \\ 1 \end{bmatrix}$

Calculate AC , B^2C and A^2B^2C . Also, verify that $A^2B^2C = AC = B^2C$

Solution Now, $A^2B^2C = \begin{bmatrix} 1 & 1 & 1 \\ -5 & 1 & 1 \\ 1 & -6 & 1 \end{bmatrix}$

So $A^2B^2C = \begin{bmatrix} 1 & 1 & 1 \\ -5 & 1 & 1 \\ 1 & -6 & 1 \end{bmatrix} \begin{bmatrix} 1 \\ -1 \\ 1 \end{bmatrix} = \begin{bmatrix} 1-1+1 \\ -1+1+1 \\ 16+1+1 \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 18 \end{bmatrix}$

Further $AC = \begin{bmatrix} 1 & 6 & 1 \\ -6 & 1 & 1 \\ 1 & -1 & 1 \end{bmatrix} \begin{bmatrix} 1 \\ -1 \\ 1 \end{bmatrix} = \begin{bmatrix} 1-1+1 \\ -1+1+1 \\ 1+16+1 \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 18 \end{bmatrix}$

and $B^2C = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} 1 \\ -1 \\ 1 \end{bmatrix} = \begin{bmatrix} 1-1+1 \\ 1+1+6 \\ 1-1+1 \end{bmatrix} = \begin{bmatrix} 1 \\ 8 \\ -1 \end{bmatrix}$

So $AC = B^2C = \begin{bmatrix} 1 \\ 1 \\ 18 \end{bmatrix} + \begin{bmatrix} 1 \\ 1 \\ -1 \end{bmatrix} = \begin{bmatrix} 2 \\ 2 \\ 17 \end{bmatrix}$

Clearly, $A^2B^2C = AC = B^2C$

Example 18 If $A = \begin{bmatrix} 1 & 1 & 1 \\ 1 & -1 & 1 \\ 1 & 1 & 1 \end{bmatrix}$, then show that $A^3 = 3A^2 - 6A + 6I$

Solution We have $A^3 = A.A^2 = \begin{bmatrix} 1 & 1 & 1 \\ 1 & -1 & 1 \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} 1 & 1 & 1 \\ 1 & -1 & 1 \\ 1 & 1 & 1 \end{bmatrix} = \begin{bmatrix} 3 & 1 & 3 \\ 1 & 1 & 3 \\ 3 & 6 & 3 \end{bmatrix}$

So
$$A^{-1} = A^{-1} A^{-1} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & -1 & 1 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 1 & 1 & 0 \\ 1 & 6 & 15 \end{bmatrix} = \begin{bmatrix} 6 & 6 & 6 \\ 6 & -6 & 0 \\ 0 & 6 & 6 \end{bmatrix}$$

Now

$$\begin{aligned} A^{-1} A^{-1} A^{-1} &= \begin{bmatrix} 6 & 6 & 6 \\ 6 & -6 & 0 \\ 0 & 6 & 6 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & -1 & 1 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \\ &= \begin{bmatrix} 6 & 6 & 6 \\ 6 & -6 & 0 \\ 0 & 6 & 6 \end{bmatrix} + \begin{bmatrix} -6 & -6 & -6 \\ -6 & 6 & -6 \\ -6 & -6 & -6 \end{bmatrix} + \begin{bmatrix} -6 & 0 & 0 \\ 0 & -6 & 0 \\ 0 & 0 & -6 \end{bmatrix} \\ &= \begin{bmatrix} 6-6-6 & 6-6+0 & 6-6+0 \\ 6-6+0 & -6+6-6 & 0-6+0 \\ 0-6+0 & 6-6+0 & 6-6-6 \end{bmatrix} \\ &= \begin{bmatrix} -6 & 0 & 0 \\ 0 & -6 & -6 \\ 0 & 0 & -6 \end{bmatrix} = \square \end{aligned}$$

Example 19 In a legislative assembly election, a political group hired a public relations firm to promote its candidate in three ways—telephone, house calls, and letters. The cost per contact in paise is given in matrix A as

$$A = \begin{bmatrix} \square & \square & \square \\ 1 & \square & \square \\ 5 & \square & \square \end{bmatrix} \begin{matrix} \text{Telephone} \\ \text{Housecall} \\ \text{Letter} \end{matrix}$$

The number of contacts of each type made in two cities □ and □ is given by

$$\square = \begin{matrix} \text{Telephone} & \text{Housecall} & \text{Letter} \\ \begin{bmatrix} 1 & \square & \square \\ \square & \square & \square \end{bmatrix} \rightarrow \square \\ \begin{bmatrix} \square & \square & \square \\ \square & \square & \square \end{bmatrix} \rightarrow \square \end{matrix} . \text{ Find the total amount spent by the group in the two}$$

cities □ and □.

Solution We have

$$\begin{aligned}
 A &= \begin{bmatrix} 1000 + 5000 + 5000 & 1000 + 5000 \\ 1000 + 5000 & 1000 + 5000 \end{bmatrix} \rightarrow \begin{bmatrix} 10000 & 10000 \\ 10000 & 10000 \end{bmatrix} \\
 &= \begin{bmatrix} 10000 & 10000 \\ 10000 & 10000 \end{bmatrix} \rightarrow \begin{bmatrix} 10000 & 10000 \\ 10000 & 10000 \end{bmatrix}
 \end{aligned}$$

So the total amount spent by the group in the two cities is 10000 paise and 10000 paise, i.e., Rs 1000 and Rs 1000, respectively.

EXERCISE 3.2

1. Let $A = \begin{bmatrix} a & b \\ c & d \end{bmatrix}$, $B = \begin{bmatrix} 1 & 2 \\ -3 & 5 \end{bmatrix}$, $C = \begin{bmatrix} -4 & 5 \\ 6 & 7 \end{bmatrix}$

Find each of the following

- i) $A + B$ ii) $A - B$ iii) $A + C$
- iv) $A - C$ v) $C - A$

2. Compute the following

- i) $\begin{bmatrix} a & b \\ -b & a \end{bmatrix} + \begin{bmatrix} a & b \\ b & a \end{bmatrix}$ ii) $\begin{bmatrix} a^2 + b^2 & b^2 + c^2 \\ a^2 + c^2 & a^2 + b^2 \end{bmatrix} + \begin{bmatrix} ab & bc \\ -ac & -ab \end{bmatrix}$
- iii) $\begin{bmatrix} -1 & 2 & -6 \\ 3 & 5 & 16 \\ 4 & 7 & 5 \end{bmatrix} + \begin{bmatrix} 1 & 3 & 6 \\ 2 & 4 & 5 \\ 3 & 5 & 7 \end{bmatrix}$ iv) $\begin{bmatrix} \cos^2 x & \sin^2 x \\ \sin^2 x & \cos^2 x \end{bmatrix} + \begin{bmatrix} \sin^2 x & \cos^2 x \\ \cos^2 x & \sin^2 x \end{bmatrix}$

3. Compute the indicated products.

- i) $\begin{bmatrix} a & b \\ -b & a \end{bmatrix} \begin{bmatrix} a & -b \\ b & a \end{bmatrix}$ ii) $\begin{bmatrix} 1 \\ 2 \\ 3 \end{bmatrix} \begin{bmatrix} 4 & 5 & 6 \end{bmatrix}$ iii) $\begin{bmatrix} 1 & -2 \\ 3 & 4 \end{bmatrix} \begin{bmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \end{bmatrix}$
- iv) $\begin{bmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \\ 7 & 8 & 9 \end{bmatrix} \begin{bmatrix} 1 & -2 & 3 \\ 4 & 5 & 6 \\ 7 & 8 & 9 \end{bmatrix}$ v) $\begin{bmatrix} 1 & 1 \\ 2 & 2 \\ -1 & 1 \end{bmatrix} \begin{bmatrix} 1 & 2 & 3 \\ -1 & 2 & 1 \end{bmatrix}$
- vi) $\begin{bmatrix} 1 & -1 & 2 \\ -1 & 2 & 3 \end{bmatrix} \begin{bmatrix} 2 & -3 \\ 1 & 4 \\ 3 & 1 \end{bmatrix}$

4. If $A = \begin{bmatrix} 1 & \square & -\square \\ 5 & \square & \square \\ 1 & -1 & 1 \end{bmatrix}$, $B = \begin{bmatrix} \square & -1 & \square \\ \square & \square & 5 \\ \square & \square & \square \end{bmatrix}$ and $C = \begin{bmatrix} \square & 1 & \square \\ \square & \square & \square \\ 1 & -\square & \square \end{bmatrix}$, then compute

$A + B$ and $B + C$. Also, verify that $A + (B + C) = (A + B) + C$.

5. If $A = \begin{bmatrix} \square & 1 & 5 \\ \square & \square & \square \\ 1 & \square & \square \\ \square & \square & \square \\ \square & \square & \square \end{bmatrix}$ and $B = \begin{bmatrix} \square & \square & 1 \\ 5 & 5 & \square \\ 1 & \square & \square \\ \square & 6 & \square \\ 5 & 5 & 5 \end{bmatrix}$, then compute $A + 5B$.

6. Simplify $\cos\theta \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} + \sin\theta \begin{bmatrix} \sin\theta & -\cos\theta \\ \cos\theta & \sin\theta \end{bmatrix}$

7. Find \square and \square , if

(i) $\square \square \square = \begin{bmatrix} \square & \square \\ \square & 5 \end{bmatrix}$ and $\square \square \square = \begin{bmatrix} \square & \square \\ \square & \square \end{bmatrix}$

(ii) $\square \square \square \square = \begin{bmatrix} \square & \square \\ \square & \square \end{bmatrix}$ and $\square \square + \square \square = \begin{bmatrix} \square & -\square \\ -1 & 5 \end{bmatrix}$

8. Find \square , if $\square \square \begin{bmatrix} \square & \square \\ 1 & \square \end{bmatrix}$ and $\square \square \square \square \begin{bmatrix} 1 & \square \\ -\square & \square \end{bmatrix}$

9. Find x and y , if $\square \begin{bmatrix} 1 & \square \\ \square & x \end{bmatrix} + \begin{bmatrix} y & \square \\ 1 & \square \end{bmatrix} = \begin{bmatrix} 5 & 6 \\ 1 & \square \end{bmatrix}$

10. Solve the equation for x, y, z and t , if $\square \begin{bmatrix} x & z \\ y & t \end{bmatrix} + \square \begin{bmatrix} 1 & -1 \\ \square & \square \end{bmatrix} = \square \begin{bmatrix} \square & 5 \\ \square & 6 \end{bmatrix}$

11. If $x \begin{bmatrix} \square \\ \square \end{bmatrix} + y \begin{bmatrix} -1 \\ 1 \end{bmatrix} = \begin{bmatrix} 1 \square \\ 5 \end{bmatrix}$, find the values of x and y .

12. Given $\square \begin{bmatrix} x & y \\ z & w \end{bmatrix} = \begin{bmatrix} x & 6 \\ -1 & \square w \end{bmatrix} + \begin{bmatrix} \square & x+y \\ z+w & \square \end{bmatrix}$, find the values of x, y, z and w .

13. If $\begin{bmatrix} \cos x & -\sin x \\ \sin x & \cos x \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} x \\ y \end{bmatrix}$, show that $\begin{bmatrix} \cos x & -\sin x \\ \sin x & \cos x \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} x \\ y \end{bmatrix}$

14. Show that

i) $\begin{bmatrix} 5 & -1 \\ 6 & \end{bmatrix} \begin{bmatrix} 1 \\ \end{bmatrix} \neq \begin{bmatrix} 1 \\ \end{bmatrix} \begin{bmatrix} 5 & -1 \\ 6 & \end{bmatrix}$

ii) $\begin{bmatrix} 1 & \end{bmatrix} \begin{bmatrix} -1 & 1 \\ \end{bmatrix} \neq \begin{bmatrix} -1 & 1 \\ \end{bmatrix} \begin{bmatrix} 1 & \end{bmatrix}$

15. Find A^{-1} if $A = \begin{bmatrix} 5 & 6 \\ 1 & -1 \end{bmatrix}$

16. If $A = \begin{bmatrix} 1 & \end{bmatrix}$, prove that $A^{-1} = 6A^{-1} - A - I$

17. If $A = \begin{bmatrix} \end{bmatrix}$ and $I = \begin{bmatrix} 1 & \end{bmatrix}$, find k so that $A^{-1} = kA - I$

18. If $A = \begin{bmatrix} \end{bmatrix}$ and I is the identity matrix of order n , show that

$$I - A = I - A = \begin{bmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{bmatrix}$$

19. A trust fund has Rs 1000 that must be invested in two different types of bonds. The first bond pays 5% interest per year, and the second bond pays 7% interest per year. Using matrix multiplication, determine how to divide Rs 1000 among the two types of bonds. If the trust fund must obtain an annual total interest of

- a) Rs 100
- b) Rs 1000

Solution

□ We have

$$A = \begin{bmatrix} \square & \sqrt{\square} & \square \\ \square & \square & \square \end{bmatrix} \Rightarrow A' = \begin{bmatrix} \square & \square \\ \sqrt{\square} & \square \\ \square & \square \end{bmatrix} \Rightarrow (A')' = \begin{bmatrix} \square & \sqrt{\square} & \square \\ \square & \square & \square \end{bmatrix} = A$$

Thus □A'□□A

□ We have

$$A = \begin{bmatrix} \square & \sqrt{\square} & \square \\ \square & \square & \square \end{bmatrix}, \square = \begin{bmatrix} \square & -1 & \square \\ 1 & \square & \square \end{bmatrix} \Rightarrow A + \square = \begin{bmatrix} 5 & \sqrt{\square}-1 & \square \\ 5 & \square & \square \end{bmatrix}$$

Therefore □A □□□□□ $\begin{bmatrix} 5 & 5 \\ \sqrt{\square}-1 & \square \\ \square & \square \end{bmatrix}$

Now □A'□□□□□ $\begin{bmatrix} \square & \square \\ \sqrt{\square} & \square \\ \square & \square \end{bmatrix}, \square' = \begin{bmatrix} \square & 1 \\ -1 & \square \\ \square & \square \end{bmatrix},$

So □A' □□□' □ $\begin{bmatrix} 5 & 5 \\ \sqrt{\square}-1 & \square \\ \square & \square \end{bmatrix}$

Thus □A □□□□□A' □□□'

□ We have

$$k = k \begin{bmatrix} \square & -1 & \square \\ 1 & \square & \square \end{bmatrix} = \begin{bmatrix} \square k & -k & \square k \\ k & \square k & \square k \end{bmatrix}$$

Then □k□□□□□ $\begin{bmatrix} \square k & k \\ -k & \square k \\ \square k & \square k \end{bmatrix} = k \begin{bmatrix} \square & 1 \\ -1 & \square \\ \square & \square \end{bmatrix} = k \square'$

Thus □k□□□□k□'

Example 21 If $A = \begin{bmatrix} -1 \\ 1 \\ 5 \end{bmatrix}$, $\alpha = [1 \quad 1 \quad -6]$, verify that $\alpha A \alpha \alpha' A'$.

Solution We have

$$A = \begin{bmatrix} -1 \\ 1 \\ 5 \end{bmatrix}, \alpha = [1 \quad 1 \quad -6]$$

then $\alpha A = \begin{bmatrix} -1 \\ 1 \\ 5 \end{bmatrix} [1 \quad 1 \quad -6] = \begin{bmatrix} -1 & -6 & 1 \\ 1 & 1 & -6 \\ 5 & 15 & -6 \end{bmatrix}$

Now $A' = [1 \quad 1 \quad 5]$, $\alpha' = \begin{bmatrix} 1 \\ 1 \\ -6 \end{bmatrix}$

$$\alpha' A' = \begin{bmatrix} 1 \\ 1 \\ -6 \end{bmatrix} [1 \quad 1 \quad 5] = \begin{bmatrix} -1 & 1 & 5 \\ -6 & 1 & 15 \\ 1 & -1 & -1 \end{bmatrix} = \alpha A \alpha'$$

Clearly $\alpha A \alpha \alpha' A'$

3.6 Symmetric and Skew Symmetric Matrices

Definition 4 A square matrix $A = [a_{ij}]$ is said to be *symmetric* if $A' = A$, that is, $[a_{ij}] = [a_{ji}]$ for all possible values of i and j .

For example $A = \begin{bmatrix} \sqrt{2} & 1 & 1 \\ 1 & -1.5 & -1 \\ 1 & -1 & 1 \end{bmatrix}$ is a symmetric matrix as $A' = A$

Definition 5 A square matrix $A = [a_{ij}]$ is said to be *skew symmetric* matrix if $A' = -A$, that is $a_{ji} = -a_{ij}$ for all possible values of i and j . Now, if we put $i = j$, we have $a_{ii} = -a_{ii}$. Therefore $a_{ii} = 0$ or $a_{ii} = 0$ for all $i \in \mathbb{R}$.

This means that all the diagonal elements of a skew symmetric matrix are zero.

For example, the matrix $A = \begin{bmatrix} e & f \\ -e & g \\ -f & -g \end{bmatrix}$ is a skew symmetric matrix as $A' = -A$.

Now, we are going to prove some results of symmetric and skew-symmetric matrices.

Theorem 1 For any square matrix A with real number entries, $A + A'$ is a symmetric matrix and $A - A'$ is a skew symmetric matrix.

Proof Let $A = [a_{ij}]$, then

$$\begin{aligned} (A + A')' &= (A + A') \\ &= A' + (A')' \text{ as } (A + A')' = A' + (A')' \\ &= A' + A \text{ as } (A')' = A \\ &= A + A' \text{ as } A' + A = A + A' \\ &= A + A' \end{aligned}$$

Therefore $A + A'$ is a symmetric matrix

Now let

$$\begin{aligned} C &= A - A' \\ C' &= (A - A')' = A' - (A')' \text{ Why?} \\ &= A' - A \text{ Why?} \\ &= -(A - A') = -C \end{aligned}$$

Therefore $A - A'$ is a skew symmetric matrix.

Theorem 2 Any square matrix can be expressed as the sum of a symmetric and a skew symmetric matrix.

Proof Let A be a square matrix, then we can write

$$A = \frac{1}{2}(A + A') + \frac{1}{2}(A - A')$$

From the Theorem 1, we know that $\frac{1}{2}(A + A')$ is a symmetric matrix and $\frac{1}{2}(A - A')$ is a skew symmetric matrix. Since for any matrix A , $kA = (kA)$, it follows that $\frac{1}{2}(A + A')$

is symmetric matrix and $\frac{1}{2}(A - A')$ is skew symmetric matrix. Thus, any square matrix can be expressed as the sum of a symmetric and a skew symmetric matrix.

Example 22 Express the matrix $A = \begin{bmatrix} 1 & -1 & -1 \\ -1 & 1 & 1 \\ 1 & -1 & 1 \end{bmatrix}$ as the sum of a symmetric and a skew symmetric matrix.

Solution Here

$$A = \begin{bmatrix} 1 & -1 & -1 \\ -1 & 1 & 1 \\ -1 & 1 & 1 \end{bmatrix}$$

Let $A = \frac{1}{2}(A + A') + \frac{1}{2}(A - A')$ $= \frac{1}{2} \begin{bmatrix} 1 & -1 & -1 \\ -1 & 1 & 1 \\ -1 & 1 & 1 \end{bmatrix} + \frac{1}{2} \begin{bmatrix} 0 & -2 & -2 \\ 2 & 0 & 0 \\ 2 & 0 & 0 \end{bmatrix}$,

Now $\frac{1}{2} \begin{bmatrix} 1 & -1 & -1 \\ -1 & 1 & 1 \\ -1 & 1 & 1 \end{bmatrix}$ is a symmetric matrix.

Thus $\frac{1}{2} \begin{bmatrix} 1 & -1 & -1 \\ -1 & 1 & 1 \\ -1 & 1 & 1 \end{bmatrix}$ is a symmetric matrix.

Also, let $A = \frac{1}{2}(A + A') + \frac{1}{2}(A - A')$ $= \frac{1}{2} \begin{bmatrix} 1 & -1 & -5 \\ 1 & 1 & 6 \\ 5 & -6 & 1 \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 & -1 & -5 \\ 1 & 1 & 6 \\ 5 & -6 & 1 \end{bmatrix}$

Then $\frac{1}{2} \begin{bmatrix} 1 & -1 & -5 \\ 1 & 1 & 6 \\ 5 & -6 & 1 \end{bmatrix}$ is a skew symmetric matrix.

Thus $\frac{1}{c} \begin{bmatrix} a & b & c \\ -b & a & c \\ c & -c & 0 \end{bmatrix}$ is a skew symmetric matrix.

Now
$$\begin{bmatrix} a & b & c \\ -b & a & c \\ c & -c & 0 \end{bmatrix} = \begin{bmatrix} a & \frac{-b}{c} & \frac{-c}{c} \\ \frac{-b}{c} & a & 1 \\ \frac{-c}{c} & 1 & -1 \end{bmatrix} + \begin{bmatrix} a & \frac{-1}{c} & \frac{-5}{c} \\ \frac{1}{c} & a & c \\ \frac{5}{c} & -1 & c \end{bmatrix} = \begin{bmatrix} a & -b & -c \\ -1 & a & c \\ 1 & -c & -1 \end{bmatrix} = A$$

Thus, A is represented as the sum of a symmetric and a skew symmetric matrix.

EXERCISE 3.3

1. Find the transpose of each of the following matrices

i $\begin{bmatrix} 5 \\ 1 \\ c \\ -1 \end{bmatrix}$ ii $\begin{bmatrix} 1 & -1 \\ a & c \end{bmatrix}$ iii $\begin{bmatrix} -1 & 5 & 6 \\ \sqrt{c} & 5 & 6 \\ a & a & -1 \end{bmatrix}$

2. If $A = \begin{bmatrix} -1 & a & a \\ 5 & a & a \\ -a & 1 & 1 \end{bmatrix}$ and $B = \begin{bmatrix} -a & 1 & -5 \\ 1 & a & c \\ 1 & a & 1 \end{bmatrix}$, then verify that
 i $A + B = (A + B)'$, ii $A - B = (A - B)'$

3. If $A' = \begin{bmatrix} a & a \\ -1 & a \\ a & 1 \end{bmatrix}$ and $B = \begin{bmatrix} -1 & a & 1 \\ 1 & a & c \end{bmatrix}$, then verify that
 i $A + B = (A + B)'$ ii $A - B = (A - B)'$

4. If $A' = \begin{bmatrix} -a & a \\ 1 & a \end{bmatrix}$ and $B = \begin{bmatrix} -1 & a \\ 1 & a \end{bmatrix}$, then find $(A + B)'$

5. For the matrices A and B , verify that $(A + B)' = A' + B'$, where

i $A = \begin{bmatrix} 1 \\ -a \\ a \end{bmatrix}$, $B = [-1 \ a \ 1]$ ii $A = \begin{bmatrix} a \\ 1 \\ a \end{bmatrix}$, $B = [1 \ 5 \ c]$

6. If $A = \begin{bmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{bmatrix}$, then verify that $A' A = I$

ii If $A = \begin{bmatrix} \sin \alpha & \cos \alpha \\ -\cos \alpha & \sin \alpha \end{bmatrix}$, then verify that $A' A = I$

7. i Show that the matrix $A = \begin{bmatrix} 1 & -1 & 5 \\ -1 & \square & 1 \\ 5 & 1 & \square \end{bmatrix}$ is a symmetric matrix.

ii Show that the matrix $A = \begin{bmatrix} \square & 1 & -1 \\ -1 & \square & 1 \\ 1 & -1 & \square \end{bmatrix}$ is a skew symmetric matrix.

8. For the matrix $A = \begin{bmatrix} 1 & 5 \\ 6 & \square \end{bmatrix}$, verify that

i $A + A'$ is a symmetric matrix

ii $A - A'$ is a skew symmetric matrix

9. Find $\frac{1}{2}(A + A')$ and $\frac{1}{2}(A - A')$, when $A = \begin{bmatrix} \square & a & b \\ -a & \square & c \\ -b & -c & \square \end{bmatrix}$

10. Express the following matrices as the sum of a symmetric and a skew symmetric matrix

i $\begin{bmatrix} \square & 5 \\ 1 & -1 \end{bmatrix}$

ii $\begin{bmatrix} 6 & -\square & \square \\ -\square & \square & -1 \\ \square & -1 & \square \end{bmatrix}$

iii $\begin{bmatrix} \square & \square & -1 \\ -\square & -\square & 1 \\ -\square & -5 & \square \end{bmatrix}$

iv $\begin{bmatrix} 1 & 5 \\ -1 & \square \end{bmatrix}$

Choose the correct answer in the Exercises 11 and 1□

11. If A, □ are symmetric matrices of same order, then A□ □ □A is a

- A □ Skew symmetric matrix □ □ Symmetric matrix
 C □ □ero matrix □ □ Identity matrix

12. If $A = \begin{bmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{bmatrix}$, then $A \square A' \square I$, if the value of α is

- A □ $\frac{\pi}{6}$ □ □ $\frac{\pi}{\square}$
 C □ π □ □ $\frac{\square \pi}{\square}$

3.7 Elementary Operation (Transformation) of a Matrix

There are six operations □transformations□ on a matrix, three of which are due to rows and three due to columns, which are known as *elementary operations* or *transformations*.

□i□ *The interchange of any two rows or two columns.* Symbolically the interchange of i^{th} and j^{th} rows is denoted by $R_i \leftrightarrow R_j$ and interchange of i^{th} and j^{th} column is denoted by $C_i \leftrightarrow C_j$.

□or example, applying $R_1 \leftrightarrow R_2$ to $A = \begin{bmatrix} 1 & \square & 1 \\ -1 & \sqrt{\square} & 1 \\ 5 & 6 & \square \end{bmatrix}$, we get $\begin{bmatrix} -1 & \sqrt{\square} & 1 \\ 1 & \square & 1 \\ 5 & 6 & \square \end{bmatrix}$.

□ii□ *The multiplication of the elements of any row or column by a non zero number.* Symbolically, the multiplication of each element of the i^{th} row by k , where $k \neq \square$ is denoted by $R_i \rightarrow kR_i$.

The corresponding column operation is denoted by $C_i \rightarrow kC_i$

□or example, applying $C_2 \rightarrow \frac{1}{\square}C_2$, to $\square = \begin{bmatrix} 1 & \square & 1 \\ -1 & \sqrt{\square} & 1 \\ \square & \square & \square \end{bmatrix}$, we get $\begin{bmatrix} 1 & \square & \frac{1}{\square} \\ -1 & \sqrt{\square} & \frac{1}{\square} \\ \square & \square & \square \end{bmatrix}$

□iii□ *The addition to the elements of any row or column, the corresponding elements of any other row or column multiplied by any non zero number.*

Symbolically, the addition to the elements of i^{th} row, the corresponding elements of j^{th} row multiplied by k is denoted by $R_i \rightarrow R_i \square kR_j$.

The corresponding column operation is denoted by $C_i \rightarrow C_i + kC_j$.

For example, applying $R_2 \rightarrow R_2 + R_1$, to $C = \begin{bmatrix} 1 & 2 \\ 3 & -1 \end{bmatrix}$, we get $\begin{bmatrix} 1 & 2 \\ 4 & -5 \end{bmatrix}$.

3.8 Invertible Matrices

Definition 6 If A is a square matrix of order m , and if there exists another square matrix B of the same order m , such that $AB = BA = I$, then B is called the *inverse* matrix of A and it is denoted by A^{-1} . In that case A is said to be invertible.

For example, let $A = \begin{bmatrix} 1 & 2 \\ 3 & 4 \end{bmatrix}$ and $B = \begin{bmatrix} -2 & 1 \\ 1 & -1 \end{bmatrix}$ be two matrices.

Now $AB = \begin{bmatrix} 1 & 2 \\ 3 & 4 \end{bmatrix} \begin{bmatrix} -2 & 1 \\ 1 & -1 \end{bmatrix} = \begin{bmatrix} -2+2 & 1-2 \\ -6+4 & -3+4 \end{bmatrix} = \begin{bmatrix} 0 & -1 \\ -2 & 1 \end{bmatrix} \neq I$

$BA = \begin{bmatrix} -2 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} 1 & 2 \\ 3 & 4 \end{bmatrix} = \begin{bmatrix} -2+3 & -4+4 \\ -1+3 & -2+4 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 2 & 2 \end{bmatrix} \neq I$

Also $BA = \begin{bmatrix} -2 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} 1 & 2 \\ 3 & 4 \end{bmatrix} = I$. Thus B is the inverse of A , in other words $B = A^{-1}$ and A is inverse of B , i.e., $A = B^{-1}$

Note

1. A rectangular matrix does not possess inverse matrix, since for products BA and AB to be defined and to be equal, it is necessary that matrices A and B should be square matrices of the same order.
- If B is the inverse of A , then A is also the inverse of B .

Theorem 3 Uniqueness of inverse Inverse of a square matrix, if it exists, is unique.

Proof Let $A = [a_{ij}]$ be a square matrix of order m . If possible, let B and C be two inverses of A . We shall show that $B = C$.

Since B is the inverse of A $AB = BA = I$... (1)

Since C is also the inverse of A $AC = CA = I$... (2)

Thus $AB = I = AC \implies A(B - C) = I - I = O \implies A(B - C) = O$

Theorem 4 If A and B are invertible matrices of the same order, then $(A^{-1})^{-1} = A$.

Proof From the definition of inverse of a matrix, we have

$$A^{-1}A = I$$

or $A^{-1}A^{-1}A = A^{-1}I$ [Multiplying both sides by A^{-1}]

or $A^{-1}A = A^{-1}$ [Since $A^{-1}I = A^{-1}$]

or $I = A^{-1}$

or $A^{-1} = I$

or $A^{-1} = I$

or $I = A^{-1}$

Hence $A^{-1} = I$

3.8.1 Inverse of a matrix by elementary operations

Let A , X and Y be matrices of the same order such that $AX = Y$. In order to apply a sequence of elementary row operations on the matrix equation $AX = Y$, we will apply these row operations simultaneously on X and on the first matrix A of the product AX on RHS.

Similarly, in order to apply a sequence of elementary column operations on the matrix equation $AX = Y$, we will apply these operations simultaneously on X and on the second matrix X of the product AX on RHS.

In view of the above discussion, we conclude that if A is a matrix such that A^{-1} exists, then to find A^{-1} using elementary row operations, write $A^{-1}A = I$ and apply a sequence of row operation on $A^{-1}A$ till we get, $I = A^{-1}A$. The matrix A^{-1} will be the inverse of A . Similarly, if we wish to find A^{-1} using column operations, then, write $A^{-1}A = I$ and apply a sequence of column operations on $A^{-1}A$ till we get, $I = A^{-1}A$.

Remark In case, after applying one or more elementary row [column] operations on $A^{-1}A = I$ if we obtain all [zeros] in one or more rows of the matrix A on L.H.S., then A^{-1} does not exist.

Example 23 By using elementary operations, find the inverse of the matrix

$$A = \begin{bmatrix} 1 & 2 \\ 3 & -1 \end{bmatrix}$$

Solution In order to use elementary row operations we may write $A^{-1}A = I$.

or $\begin{bmatrix} 1 & 2 \\ 3 & -1 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} A$, then $\begin{bmatrix} 1 & 2 \\ 3 & -1 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -3 & 1 \end{bmatrix} A$ [applying $R_2 \rightarrow R_2 - 3R_1$]

or
$$\begin{bmatrix} 1 & \square \\ \square & 1 \end{bmatrix} \square \begin{bmatrix} 1 & \square \\ \square & -1 \\ \square & 5 \end{bmatrix} A \text{ [applying } R_2 \rightarrow \square \frac{1}{5} R_2 \text{]}$$

or
$$\begin{bmatrix} 1 & \square \\ \square & 1 \end{bmatrix} \square \begin{bmatrix} 1 & \square \\ \square & 5 \\ \square & -1 \\ \square & 5 \end{bmatrix} A \text{ [applying } R_1 \rightarrow R_1 \square \square R_2 \text{]}$$

Thus
$$A^{-1} \square \begin{bmatrix} 1 & \square \\ \square & 5 \\ \square & -1 \\ \square & 5 \end{bmatrix}$$

Alternatively, in order to use elementary column operations, we write $A \square AI$, i.e.,

$$\begin{bmatrix} 1 & \square \\ \square & -1 \end{bmatrix} \square A \begin{bmatrix} 1 & \square \\ \square & 1 \end{bmatrix}$$

Applying $C_2 \rightarrow C_2 \square \square C_1$, we get

$$\begin{bmatrix} 1 & \square \\ \square & -5 \end{bmatrix} \square A \begin{bmatrix} 1 & -\square \\ \square & 1 \end{bmatrix}$$

Now applying $C_2 \rightarrow -\frac{1}{5}C_2$, we have

$$\begin{bmatrix} 1 & \square \\ \square & 1 \end{bmatrix} \square A \begin{bmatrix} 1 & \square \\ \square & \frac{-1}{5} \end{bmatrix}$$

Finally, applying $C_1 \rightarrow C_1 \square \square C_2$, we obtain

$$\begin{bmatrix} 1 & \square \\ \square & 1 \end{bmatrix} \square A \begin{bmatrix} 1 & \square \\ \square & \frac{-1}{5} \\ \square & \frac{-1}{5} \end{bmatrix}$$

Hence
$$A^{-1} \square \begin{bmatrix} 1 & \square \\ \square & 5 \\ \square & -1 \\ \square & 5 \end{bmatrix}$$

Example 24 Obtain the inverse of the following matrix using elementary operations

$$A = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}$$

Solution Write $A \equiv IA$, i.e., $\begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix} \equiv \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} A$

or $\begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix} \equiv \begin{bmatrix} 1 & 1 & 1 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} A$ [applying $R_1 \leftrightarrow R_2$]

or $\begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & -5 & -1 \end{bmatrix} \equiv \begin{bmatrix} 1 & 1 & 1 \\ 0 & 0 & 0 \\ 0 & -6 & -2 \end{bmatrix} A$ [applying $R_2 \rightarrow R_2 - R_1$]

or $\begin{bmatrix} 1 & 1 & -1 \\ 1 & 1 & 1 \\ 1 & -5 & -1 \end{bmatrix} \equiv \begin{bmatrix} -1 & 1 & 1 \\ 0 & 0 & 0 \\ 0 & -6 & -2 \end{bmatrix} A$ [applying $R_1 \rightarrow R_1 - R_2$]

or $\begin{bmatrix} 1 & 1 & -1 \\ 1 & 1 & 1 \\ 0 & 0 & 1 \end{bmatrix} \equiv \begin{bmatrix} -1 & 1 & 1 \\ 0 & 0 & 0 \\ 5 & -6 & 1 \end{bmatrix} A$ [applying $R_2 \rightarrow R_2 - R_1$]

or $\begin{bmatrix} 1 & 1 & -1 \\ 1 & 1 & 1 \\ 0 & 0 & 1 \end{bmatrix} \equiv \begin{bmatrix} -1 & 1 & 1 \\ 1 & 0 & 0 \\ 5 & -6 & 1 \end{bmatrix} A$ [applying $R_2 \rightarrow \frac{1}{5} R_2$]

or $\begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 0 & 0 & 1 \end{bmatrix} \equiv \begin{bmatrix} 1 & -1 & 1 \\ 0 & 0 & 0 \\ 5 & -6 & 1 \end{bmatrix} A$ [applying $R_1 \rightarrow R_1 - R_2$]

or
$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cong \begin{bmatrix} 1 & -1 & 1 \\ -1 & 0 & -1 \\ 5 & -1 & 1 \end{bmatrix} \text{ A applying } R_1 \rightarrow R_1 + R_2$$

Hence
$$A^{-1} = \begin{bmatrix} 1 & -1 & 1 \\ -1 & 0 & -1 \\ 5 & -1 & 1 \end{bmatrix}$$

Alternatively, write $A = AI$, i.e.,

$$\begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 1 \end{bmatrix} = A \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

or
$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 1 & 0 & 1 \end{bmatrix} = A \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad [C_1 \leftrightarrow C_2]$$

or
$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & -1 \\ 1 & 0 & -1 \end{bmatrix} = A \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & -1 \\ 0 & 0 & 1 \end{bmatrix} \quad [C_2 \rightarrow C_2 + C_1]$$

or
$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{bmatrix} = A \begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & -1 \\ 0 & 0 & 1 \end{bmatrix} \quad [C_2 \rightarrow C_2 + C_3]$$

or
$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 1 & 0 & 1 \end{bmatrix} = A \begin{bmatrix} 0 & 1 & \frac{1}{2} \\ 1 & 0 & -1 \\ 0 & 0 & \frac{1}{2} \end{bmatrix} \quad [C_2 \rightarrow \frac{1}{2} C_2]$$

or
$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ -5 & 0 & 1 \end{bmatrix} = A \begin{bmatrix} -\frac{1}{5} & 1 & \frac{1}{5} \\ 1 & 0 & -1 \\ 0 & 0 & \frac{1}{5} \end{bmatrix} \quad [C_1 \rightarrow C_1 + 5C_3]$$

or
$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} = A \begin{bmatrix} \frac{1}{5} & 1 & \frac{1}{5} \\ -\frac{1}{5} & 0 & -1 \\ \frac{5}{5} & 0 & \frac{1}{5} \end{bmatrix} \quad [C_1 \rightarrow C_1 + 5C_3]$$

or
$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} = A \begin{bmatrix} \frac{1}{5} & -\frac{1}{5} & \frac{1}{5} \\ -\frac{1}{5} & 0 & -1 \\ \frac{5}{5} & -\frac{1}{5} & \frac{1}{5} \end{bmatrix} \quad [C_2 \rightarrow C_2 + C_3]$$

Hence
$$A^{-1} = \begin{bmatrix} \frac{1}{5} & -\frac{1}{5} & \frac{1}{5} \\ -\frac{1}{5} & 0 & -1 \\ \frac{5}{5} & -\frac{1}{5} & \frac{1}{5} \end{bmatrix}$$

Example 25 Find A^{-1} , if it exists, given $A = \begin{bmatrix} 1 & -1 \\ -5 & 1 \end{bmatrix}$.

Solution We have $AA^{-1} = I$ i.e., $\begin{bmatrix} 1 & -1 \\ -5 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$.

or
$$\begin{bmatrix} 1 & -1 \\ -5 & 1 \end{bmatrix} = \begin{bmatrix} \frac{1}{5} & 0 \\ 0 & 1 \end{bmatrix} \quad \text{[applying } R_1 \rightarrow \frac{1}{5}R_1]$$

or
$$\begin{bmatrix} 1 & -1 \\ \square & \square \end{bmatrix} \rightarrow \begin{bmatrix} 1 & \square \\ \square & 1 \end{bmatrix} \text{ applying } R_2 \rightarrow R_2 + 5R_1$$

We have all zeros in the second row of the left hand side matrix of the above equation. Therefore, A^{-1} does not exist.

EXERCISE 3.4

Using elementary transformations, find the inverse of each of the matrices, if it exists in Exercises 1 to 18.

1. $\begin{bmatrix} 1 & -1 \\ \square & \square \end{bmatrix}$

2. $\begin{bmatrix} \square & 1 \\ 1 & 1 \end{bmatrix}$

3. $\begin{bmatrix} 1 & \square \\ \square & \square \end{bmatrix}$

4. $\begin{bmatrix} \square & \square \\ 5 & \square \end{bmatrix}$

5. $\begin{bmatrix} \square & 1 \\ \square & \square \end{bmatrix}$

6. $\begin{bmatrix} \square & 5 \\ 1 & \square \end{bmatrix}$

7. $\begin{bmatrix} \square & 1 \\ 5 & \square \end{bmatrix}$

8. $\begin{bmatrix} \square & 5 \\ \square & \square \end{bmatrix}$

9. $\begin{bmatrix} \square & 1 \\ \square & \square \end{bmatrix}$

10. $\begin{bmatrix} \square & -1 \\ -\square & \square \end{bmatrix}$

11. $\begin{bmatrix} \square & -6 \\ 1 & -\square \end{bmatrix}$

12. $\begin{bmatrix} 6 & -\square \\ -\square & 1 \end{bmatrix}$

13. $\begin{bmatrix} \square & -\square \\ -1 & \square \end{bmatrix}$

14. $\begin{bmatrix} \square & 1 \\ \square & \square \end{bmatrix}$.

15. $\begin{bmatrix} \square & -\square & \square \\ \square & \square & \square \\ \square & -\square & \square \end{bmatrix}$

16. $\begin{bmatrix} 1 & \square & -\square \\ -\square & \square & -5 \\ \square & 5 & \square \end{bmatrix}$

17. $\begin{bmatrix} \square & \square & -1 \\ 5 & 1 & \square \\ \square & 1 & \square \end{bmatrix}$

18. Matrices A and B will be inverse of each other only if

(A) $AB = BA$

(B) $AB = BA = I$

(C) $AB = I, BA = I$

(D) $AB = I, BA = I$

Miscellaneous Examples

Example 26 If $A = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix}$, then prove that $A^n = \begin{bmatrix} \cos n\theta & \sin n\theta \\ -\sin n\theta & \cos n\theta \end{bmatrix}$, $n \in \mathbf{N}$.

Solution We shall prove the result by using principle of mathematical induction.

We have □ n □ If $A = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix}$, then $A^n = \begin{bmatrix} \cos n\theta & \sin n\theta \\ -\sin n\theta & \cos n\theta \end{bmatrix}$, $n \in \mathbf{N}$

$$\square \square \square A = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix}, \text{ so } A^1 = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix}$$

Therefore, the result is true for $n \square 1$.

Let the result be true for $n \square k$. So

$$\square k \square A = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix}, \text{ then } A^k = \begin{bmatrix} \cos k\theta & \sin k\theta \\ -\sin k\theta & \cos k\theta \end{bmatrix}$$

Now, we prove that the result holds for $n \square k \square 1$

$$\begin{aligned} \text{Now } A^{k+1} &= A \cdot A^k = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} \cos k\theta & \sin k\theta \\ -\sin k\theta & \cos k\theta \end{bmatrix} \\ &= \begin{bmatrix} \cos \theta \cos k\theta - \sin \theta \sin k\theta & \cos \theta \sin k\theta + \sin \theta \cos k\theta \\ -\sin \theta \cos k\theta + \cos \theta \sin k\theta & -\sin \theta \sin k\theta + \cos \theta \cos k\theta \end{bmatrix} \\ &= \begin{bmatrix} \cos [\theta + k\theta] & \sin [\theta + k\theta] \\ -\sin [\theta + k\theta] & \cos [\theta + k\theta] \end{bmatrix} = \begin{bmatrix} \cos [k+1]\theta & \sin [k+1]\theta \\ -\sin [k+1]\theta & \cos [k+1]\theta \end{bmatrix} \end{aligned}$$

Therefore, the result is true for $n \square k \square 1$. Thus by principle of mathematical induction,

we have $A^n = \begin{bmatrix} \cos n\theta & \sin n\theta \\ -\sin n\theta & \cos n\theta \end{bmatrix}$, holds for all natural numbers.

Example 27 If A and B are symmetric matrices of the same order, then show that $A+B$ is symmetric if and only if A and B commute, that is $AB = BA$.

Solution Since A and B are both symmetric matrices, therefore $A' = A$ and $B' = B$.

Let $A+B$ be symmetric, then $(A+B)' = A+B$

But $(A^{-1})^{-1} = A$ (Why?)

Therefore $A^{-1} = A$

Conversely, if $A^{-1} = A$, then we shall show that A is symmetric.

Now $(A^{-1})^{-1} = A$
 as A and A^{-1} are symmetric
 $A = A^{-1}$

Hence A is symmetric.

Example 28 Let $A = \begin{bmatrix} 1 & -1 \\ 2 & 3 \end{bmatrix}$, $B = \begin{bmatrix} 5 & 2 \\ 3 & 4 \end{bmatrix}$, $C = \begin{bmatrix} 1 & 5 \\ 2 & 3 \end{bmatrix}$. Find a matrix X such that $C = XA + B$.

Solution Since A, B, C are all square matrices of order 2 and $C = XA + B$ is well defined, X must be a square matrix of order 2.

Let $X = \begin{bmatrix} a & b \\ c & d \end{bmatrix}$. Then $C = XA + B$ gives

or $\begin{bmatrix} 1 & 5 \\ 2 & 3 \end{bmatrix} \begin{bmatrix} a & b \\ c & d \end{bmatrix} = \begin{bmatrix} 1 & -1 \\ 2 & 3 \end{bmatrix} \begin{bmatrix} 5 & 2 \\ 3 & 4 \end{bmatrix} + \begin{bmatrix} 5 & 2 \\ 3 & 4 \end{bmatrix}$

or $\begin{bmatrix} a+5c & b+5d \\ a+c & b+d \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 2 & 17 \end{bmatrix} + \begin{bmatrix} 5 & 2 \\ 3 & 4 \end{bmatrix}$

or $\begin{bmatrix} a+5c-6 & b+5d-7 \\ a+c-8 & b+d-11 \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 2 & 17 \end{bmatrix}$

By equality of matrices, we get

$$a + 5c - 6 = 1 \quad \dots (1)$$

$$a + c - 8 = 2 \quad \dots (2)$$

$$b + 5d - 7 = 1 \quad \dots (3)$$

and $b + d - 11 = 17 \quad \dots (4)$

Solving (1) and (2), we get $a = 11, c = 1$. Solving (3) and (4), we get $b = 11, d = 1$.

Therefore $X = \begin{bmatrix} a & b \\ c & d \end{bmatrix} = \begin{bmatrix} 11 & 11 \\ 1 & 1 \end{bmatrix}$

Miscellaneous Exercise on Chapter 3

1. Let $A = \begin{bmatrix} a & 1 \\ b & a \end{bmatrix}$, show that $a^n I - bA^n = a^n I - na^{n-1}bA$, where I is the identity matrix of order 2 and $n \in \mathbf{N}$.

2. If $A = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}$, prove that $A^n = \begin{bmatrix} n^{n-1} & n^{n-1} & n^{n-1} \\ n^{n-1} & n^{n-1} & n^{n-1} \\ n^{n-1} & n^{n-1} & n^{n-1} \end{bmatrix}$, $n \in \mathbf{N}$.

3. If $A = \begin{bmatrix} a & -a \\ 1 & -1 \end{bmatrix}$, then prove that $A^n = \begin{bmatrix} 1 + na & -na \\ n & 1 - na \end{bmatrix}$, where n is any positive integer.

4. If A and B are symmetric matrices, prove that $A - B$ is a skew symmetric matrix.
5. Show that the matrix A' is symmetric or skew symmetric according as A is symmetric or skew symmetric.

6. Find the values of x, y, z if the matrix $A = \begin{bmatrix} a & y & z \\ x & y & -z \\ x & -y & z \end{bmatrix}$ satisfy the equation

$$A'A = I.$$

7. For what values of x is $\begin{bmatrix} 1 & a & a \\ a & a & 1 \\ 1 & a & a \end{bmatrix} \begin{bmatrix} a \\ a \\ x \end{bmatrix} = \begin{bmatrix} a \\ a \\ a \end{bmatrix}$?

8. If $A = \begin{bmatrix} a & 1 \\ -1 & a \end{bmatrix}$, show that $A^5 - 5A + 4I = 0$.

9. Find x , if $\begin{bmatrix} 1 & a & a \\ a & a & 1 \\ a & a & a \end{bmatrix} \begin{bmatrix} x \\ a \\ 1 \end{bmatrix} = \begin{bmatrix} a \\ a \\ a \end{bmatrix}$.

- ◆ $A = [a_{ij}]_{n \times n}$ is a scalar matrix if $a_{ij} = k$, when $i \neq j$, $a_{ij} = k$, k is some constant, when $i = j$.
- ◆ $A = [a_{ij}]_{n \times n}$ is an identity matrix, if $a_{ij} = 1$, when $i = j$, $a_{ij} = 0$, when $i \neq j$.
- ◆ A zero matrix has all its elements as zero.
- ◆ $A = [a_{ij}]$ and $B = [b_{ij}]$ are of same order, if $a_{ij} = b_{ij}$ for all possible values of i and j .
- ◆ $kA = [k a_{ij}]_{m \times n}$
- ◆ $A + I = [a_{ij} + 1]$
- ◆ $A - I = [a_{ij} - 1]$
- ◆ $A + I = I + A$
- ◆ $k(A + I) = kA + kI$, where A , I and C are of same order.
- ◆ $k(A - I) = kA - kI$, where A and I are of same order, k is constant.
- ◆ $lA - kA = (l - k)A$, where k and l are constant.
- ◆ If $A = [a_{ij}]_{m \times n}$ and $B = [b_{jk}]_{n \times p}$, then $AB = [c_{ik}]_{m \times p}$, where $c_{ik} = \sum_{j=1}^n a_{ij} b_{jk}$
- ◆ $(AB)C = A(BC)$, $A(B + C) = AB + AC$, $(A + B)C = AC + BC$
- ◆ If $A = [a_{ij}]_{m \times n}$, then A' or $A^T = [a_{ji}]_{n \times m}$
- ◆ $(A')' = A$, $(kA)' = kA'$, $(A + B)' = A' + B'$, $(A - B)' = A' - B'$
- ◆ A is a symmetric matrix if $A' = A$.
- ◆ A is a skew symmetric matrix if $A' = -A$.
- ◆ Any square matrix can be represented as the sum of a symmetric and a skew symmetric matrix.
- ◆ Elementary operations of a matrix are as follows
 - i) $R_i \leftrightarrow R_j$ or $C_i \leftrightarrow C_j$
 - ii) $R_i \rightarrow kR_i$ or $C_i \rightarrow kC_i$
 - iii) $R_i \rightarrow R_i + kR_j$ or $C_i \rightarrow C_i + kC_j$
- ◆ If A and B are two square matrices such that $AB = BA = I$, then B is the inverse matrix of A and is denoted by A^{-1} and A is the inverse of B .
- ◆ Inverse of a square matrix, if it exists, is unique.



DETERMINANTS

❖ *All Mathematical truths are relative and conditional.* — C.P. STEINMETZ ❖

4.1 Introduction

In the previous chapter, we have studied about matrices and algebra of matrices. We have also learnt that a system of algebraic equations can be expressed in the form of matrices. This means, a system of linear equations like

$$\begin{aligned} a_1 x + b_1 y &= c_1 \\ a_2 x + b_2 y &= c_2 \end{aligned}$$

can be represented as $\begin{bmatrix} a_1 & b_1 \\ a_2 & b_2 \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} c_1 \\ c_2 \end{bmatrix}$. Now, this system of equations has a unique solution or not, is determined by the number $a_1 b_2 - a_2 b_1$. (Recall that if

$\frac{a_1}{a_2} \neq \frac{b_1}{b_2}$ or, $a_1 b_2 - a_2 b_1 \neq 0$, then the system of linear equations has a unique solution). The number $a_1 b_2 - a_2 b_1$



P.S. Laplace
(1749-1827)

which determines uniqueness of solution is associated with the matrix $A = \begin{bmatrix} a_1 & b_1 \\ a_2 & b_2 \end{bmatrix}$ and is called the determinant of A or det A. Determinants have wide applications in Engineering, Science, Economics, Social Science, etc.

In this chapter, we shall study determinants up to order three only with real entries. Also, we will study various properties of determinants, minors, cofactors and applications of determinants in finding the area of a triangle, adjoint and inverse of a square matrix, consistency and inconsistency of system of linear equations and solution of linear equations in two or three variables using inverse of a matrix.

4.2 Determinant

To every square matrix $A = [a_{ij}]$ of order n , we can associate a number (real or complex) called determinant of the square matrix A, where $a_{ij} = (i, j)^{\text{th}}$ element of A.

This may be thought of as a function which associates each square matrix with a unique number (real or complex). If M is the set of square matrices, \mathbb{C} is the set of numbers (real or complex) and $f: M \rightarrow \mathbb{C}$ is defined by $f(A) = k$, where $A \in M$ and $k \in \mathbb{C}$, then $f(A)$ is called the determinant of A . It is also denoted by $|A|$ or $\det A$ or Δ .

$$\text{If } A = \begin{bmatrix} a & b \\ c & d \end{bmatrix}, \text{ then determinant of } A \text{ is written as } |A| = \begin{vmatrix} a & b \\ c & d \end{vmatrix} = \det(A)$$

Remarks

- (i) For matrix A , $|A|$ is read as determinant of A and not modulus of A .
- (ii) Only square matrices have determinants.

4.2.1 Determinant of a matrix of order one

Let $A = [a]$ be the matrix of order 1, then determinant of A is defined to be equal to a .

4.2.2 Determinant of a matrix of order two

Let $A = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}$ be a matrix of order 2×2 ,

then the determinant of A is defined as

$$\det(A) = |A| = \Delta = \begin{vmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{vmatrix} = a_{11}a_{22} - a_{21}a_{12}$$

Example 1 Evaluate $\begin{vmatrix} 2 & 3 \\ -1 & 2 \end{vmatrix}$.

Solution We have $\begin{vmatrix} 2 & 3 \\ -1 & 2 \end{vmatrix} = 2(2) - 3(-1) = 4 + 3 = 7$

Example 2 Evaluate $\begin{vmatrix} x & x+1 \\ x-1 & x \end{vmatrix}$

Solution We have

$$\begin{vmatrix} x & x+1 \\ x-1 & x \end{vmatrix} = x(x) - (x+1)(x-1) = x^2 - (x^2 - 1) = x^2 - x^2 + 1 = 1$$

4.2.3 Determinant of a matrix of order 3×3

Determinant of a matrix of order three can be determined by expressing it in terms of second order determinants. This is known as expansion of a determinant along a row (or a column). There are six ways of expanding a determinant of order

corresponding to each of three rows (R_1, R_2 and R_3) and three columns (C_1, C_2 and C_3) giving the same value as shown below.

Consider the determinant of square matrix $A = [a_{ij}]_{3 \times 3}$

$$\text{i.e.,} \quad \Delta = \begin{vmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{vmatrix}$$

Expansion along first Row (R_1)

Step 1 Multiply first element a_{11} of R_1 by $(-1)^{1+1} [(-1)^{\text{sum of suffixes in } a_{11}}]$ and with the second order determinant obtained by deleting the elements of first row (R_1) and first column (C_1) of Δ as a_{11} lies in R_1 and C_1 ,

$$\text{i.e.,} \quad (-1)^{1+1} a_{11} \begin{vmatrix} a_{22} & a_{23} \\ a_{32} & a_{33} \end{vmatrix}$$

Step 2 Multiply 2nd element a_{12} of R_1 by $(-1)^{1+2} [(-1)^{\text{sum of suffixes in } a_{12}}]$ and the second order determinant obtained by deleting elements of first row (R_1) and 2nd column (C_2) of Δ as a_{12} lies in R_1 and C_2 ,

$$\text{i.e.,} \quad (-1)^{1+2} a_{12} \begin{vmatrix} a_{21} & a_{23} \\ a_{31} & a_{33} \end{vmatrix}$$

Step 3 Multiply third element a_{13} of R_1 by $(-1)^{1+3} [(-1)^{\text{sum of suffixes in } a_{13}}]$ and the second order determinant obtained by deleting elements of first row (R_1) and third column (C_3) of Δ as a_{13} lies in R_1 and C_3 ,

$$\text{i.e.,} \quad (-1)^{1+3} a_{13} \begin{vmatrix} a_{21} & a_{22} \\ a_{31} & a_{32} \end{vmatrix}$$

Step 4 Now the expansion of determinant of A , that is, Δ written as sum of all three terms obtained in steps 1, 2 and 3 above is given by

$$\begin{aligned} \det A = \Delta &= (-1)^{1+1} a_{11} \begin{vmatrix} a_{22} & a_{23} \\ a_{32} & a_{33} \end{vmatrix} + (-1)^{1+2} a_{12} \begin{vmatrix} a_{21} & a_{23} \\ a_{31} & a_{33} \end{vmatrix} \\ &+ (-1)^{1+3} a_{13} \begin{vmatrix} a_{21} & a_{22} \\ a_{31} & a_{32} \end{vmatrix} \end{aligned}$$

$$\text{or} \quad \Delta = a_{11} (a_{22} a_{33} - a_{23} a_{32}) - a_{12} (a_{21} a_{33} - a_{31} a_{23}) + a_{13} (a_{21} a_{32} - a_{31} a_{22})$$

$$= a_{11} a_{22} a_{33} - a_{11} a_{23} a_{32} - a_{12} a_{21} a_{33} + a_{12} a_{23} a_{32} + a_{13} a_{21} a_{32} - a_{13} a_{23} a_{31} \quad \dots (1)$$

 **Note** We shall apply all four steps together.

Expansion along second row (R_2)

$$\Delta = \begin{vmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{vmatrix}$$

Expanding along R_2 , we get

$$\begin{aligned} \Delta &= (-1)^{2+1} a_{21} \begin{vmatrix} a_{12} & a_{13} \\ a_{32} & a_{33} \end{vmatrix} + (-1)^{2+2} a_{22} \begin{vmatrix} a_{11} & a_{13} \\ a_{31} & a_{33} \end{vmatrix} \\ &\quad + (-1)^{2+3} a_{23} \begin{vmatrix} a_{11} & a_{12} \\ a_{31} & a_{32} \end{vmatrix} \\ &= -a_{21} (a_{12} a_{33} - a_{13} a_{32}) + a_{22} (a_{11} a_{33} - a_{13} a_{31}) \\ &\quad - a_{23} (a_{11} a_{32} - a_{12} a_{31}) \\ \Delta &= -a_{21} a_{12} a_{33} + a_{21} a_{13} a_{32} + a_{22} a_{11} a_{33} - a_{22} a_{13} a_{31} - a_{23} a_{11} a_{32} \\ &\quad + a_{23} a_{12} a_{31} \\ &= a_{11} a_{22} a_{33} - a_{11} a_{23} a_{32} - a_{12} a_{21} a_{33} + a_{12} a_{23} a_{32} + a_{13} a_{21} a_{32} \\ &\quad - a_{13} a_{23} a_{31} \quad \dots (2) \end{aligned}$$

Expansion along first Column (C_1)

$$\Delta = \begin{vmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{vmatrix}$$

By expanding along C_1 , we get

$$\begin{aligned} \Delta &= a_{11} (-1)^{1+1} \begin{vmatrix} a_{22} & a_{23} \\ a_{32} & a_{33} \end{vmatrix} + a_{21} (-1)^{2+1} \begin{vmatrix} a_{12} & a_{13} \\ a_{32} & a_{33} \end{vmatrix} \\ &\quad + a_{31} (-1)^{3+1} \begin{vmatrix} a_{12} & a_{13} \\ a_{22} & a_{23} \end{vmatrix} \\ &= a_{11} (a_{22} a_{33} - a_{23} a_{32}) - a_{21} (a_{12} a_{33} - a_{13} a_{32}) + a_{31} (a_{12} a_{23} - a_{13} a_{22}) \end{aligned}$$

$$\begin{aligned} \Delta &= a_{11} a_{22} a_{33} - a_{11} a_{23} a_{32} - a_{21} a_{12} a_{33} + a_{21} a_{13} a_{32} + a_{11} a_{12} a_{23} \\ &\quad - a_{13} a_{12} a_{22} \\ &= a_{11} a_{22} a_{33} - a_{11} a_{23} a_{32} - a_{21} a_{12} a_{33} + a_{21} a_{13} a_{32} + a_{11} a_{12} a_{23} \\ &\quad - a_{13} a_{12} a_{22} \dots \end{aligned}$$

Clearly, values of Δ in (1), (2) and (3) are equal. It is left as an exercise to the reader to verify that the values of Δ by expanding along R_1, R_2 and R_3 are equal to the value of Δ obtained in (1), (2) or (3).

Hence, expanding a determinant along any row or column gives same value.

Remarks

- (i) For easier calculations, we shall expand the determinant along that row or column which contains maximum number of zeros.
- (ii) While expanding, instead of multiplying by $(-1)^{i+j}$, we can multiply by +1 or -1 according as $(i + j)$ is even or odd.

(iii) Let $A = \begin{bmatrix} 2 & 2 \\ 0 & 0 \end{bmatrix}$ and $B = \begin{bmatrix} 1 & 1 \\ 2 & 0 \end{bmatrix}$. Then, it is easy to verify that $A = 2B$. Also $\Delta A = 0 - 0 = 0$ and $\Delta B = 0 - 2 = -2$.

Observe that, $\Delta A = (-2) = 2^2 \Delta B$ or $\Delta A = 2^n \Delta B$, where $n = 2$ is the order of square matrices A and B .

In general, if $A = kB$ where A and B are square matrices of order n , then $\Delta A = k^n \Delta B$, where $n = 1, 2, \dots$

Example 3 Evaluate the determinant $\Delta = \begin{vmatrix} 1 & 2 & 0 \\ -1 & 0 & 0 \\ 0 & 1 & 0 \end{vmatrix}$.

Solution Note that in the third column, two entries are zero. So expanding along third column (0), we get

$$\begin{aligned} \Delta &= 0 \begin{vmatrix} -1 & 0 \\ 0 & 1 \end{vmatrix} - 0 \begin{vmatrix} 1 & 2 \\ 0 & 1 \end{vmatrix} + 0 \begin{vmatrix} 1 & 2 \\ -1 & 0 \end{vmatrix} \\ &= 0(-1 - 12) - 0 + 0 = 0 \end{aligned}$$

Example 4 Evaluate $\Delta = \begin{vmatrix} 0 & \sin \alpha & -\cos \alpha \\ -\sin \alpha & 0 & \sin \beta \\ \cos \alpha & -\sin \beta & 0 \end{vmatrix}$.

Solution Expanding along R_1 , we get

$$\begin{aligned}\Delta &= 0 \begin{vmatrix} 0 & \sin \beta \\ -\sin \beta & 0 \end{vmatrix} - \sin \alpha \begin{vmatrix} -\sin \alpha & \sin \beta \\ \cos \alpha & 0 \end{vmatrix} - \cos \alpha \begin{vmatrix} -\sin \alpha & 0 \\ \cos \alpha & -\sin \beta \end{vmatrix} \\ &= 0 - \sin \alpha (0 - \sin \beta \cos \alpha) - \cos \alpha (\sin \alpha \sin \beta - 0) \\ &= \sin \alpha \sin \beta \cos \alpha - \cos \alpha \sin \alpha \sin \beta = 0\end{aligned}$$

Example 5 Find values of x for which $\begin{vmatrix} x & x \\ x & 1 \end{vmatrix} = \begin{vmatrix} 2 \\ 1 \end{vmatrix}$.

Solution We have $\begin{vmatrix} x & x \\ x & 1 \end{vmatrix} = \begin{vmatrix} 2 \\ 1 \end{vmatrix}$

i.e. $x - x^2 = 2 - 1$

i.e. $x^2 = x - 1$

∴ hence $x = \pm 2\sqrt{2}$

EXERCISE 4.1

Evaluate the determinants in Exercises 1 and 2.

1. $\begin{vmatrix} 2 & 1 \\ -1 & -1 \end{vmatrix}$

2. (i) $\begin{vmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{vmatrix}$ (ii) $\begin{vmatrix} x^2 - x + 1 & x - 1 \\ x + 1 & x + 1 \end{vmatrix}$

3. If $A = \begin{bmatrix} 1 & 2 \\ 1 & 2 \end{bmatrix}$, then show that $2A \neq 2A$

4. If $A = \begin{bmatrix} 1 & 0 & 1 \\ 0 & 1 & 2 \\ 0 & 0 & 1 \end{bmatrix}$, then show that $3A \neq 2A$

5. Evaluate the determinants

(i) $\begin{vmatrix} 1 & -1 & -2 \\ 0 & 0 & -1 \\ 1 & -1 & 0 \end{vmatrix}$ (ii) $\begin{vmatrix} 1 & -1 & 1 \\ 1 & 1 & -2 \\ 2 & 1 & 1 \end{vmatrix}$

$$(iii) \begin{vmatrix} 0 & 1 & 2 \\ -1 & 0 & - \\ -2 & & 0 \end{vmatrix} \qquad (iv) \begin{vmatrix} 2 & -1 & -2 \\ 0 & 2 & -1 \\ & - & 0 \end{vmatrix}$$

6. If $A = \begin{bmatrix} 1 & 1 & -2 \\ 2 & 1 & - \\ & & - \end{bmatrix}$, find $|A|$

7. Find values of x , if

$$(i) \begin{vmatrix} 2 & \\ & 1 \end{vmatrix} = \begin{vmatrix} 2x & \\ & x \end{vmatrix} \qquad (ii) \begin{vmatrix} 2 & \\ & \end{vmatrix} = \begin{vmatrix} x & \\ & 2x \end{vmatrix}$$

8. If $\begin{vmatrix} x & 2 \\ 1 & x \end{vmatrix} = \begin{vmatrix} & 2 \\ 1 & \end{vmatrix}$, then x is equal to

- (A) (B) (C) - (D) 0

4.3 Properties of Determinants

In the previous section, we have learnt how to expand the determinants. In this section, we will study some properties of determinants which simplifies its evaluation by obtaining maximum number of zeros in a row or a column. These properties are true for determinants of any order. However, we shall restrict ourselves upto determinants of order only.

Property 1 The value of the determinant remains unchanged if its rows and columns are interchanged.

Verification Let $\Delta = \begin{vmatrix} a_1 & a_2 & a_ \\ b_1 & b_2 & b_ \\ c_1 & c_2 & c_ \end{vmatrix}$

Expanding along first row, we get

$$\begin{aligned} \Delta &= a_1 \begin{vmatrix} b_2 & b_ \\ c_2 & c_ \end{vmatrix} - a_2 \begin{vmatrix} b_1 & b_ \\ c_1 & c_ \end{vmatrix} + a_ \begin{vmatrix} b_1 & b_2 \\ c_1 & c_2 \end{vmatrix} \\ &= a_1 (b_2 c_ - b_ c_2) - a_2 (b_1 c_ - b_ c_1) + a_ (b_1 c_2 - b_2 c_1) \end{aligned}$$

By interchanging the rows and columns of Δ , we get the determinant

$$\Delta_1 = \begin{vmatrix} a_1 & b_1 & c_1 \\ a_2 & b_2 & c_2 \\ a_ & b_ & c_ \end{vmatrix}$$

Expanding Δ_1 along first column, we get

$$\Delta_1 = a_1 (b_2 c_3 - c_2 b_3) - a_2 (b_1 c_3 - b_3 c_1) + a_3 (b_1 c_2 - b_2 c_1)$$

Hence $\Delta = \Delta_1$

Remark It follows from above property that if A is a square matrix, then $\det (A) = \det (A')$, where $A' =$ transpose of A.

Note If $R_i =$ i th row and $C_i =$ i th column, then for interchange of row and columns, we will symbolically write $C_i \leftrightarrow R_i$

Let us verify the above property by example.

Example 6 Verify Property 1 for $\Delta = \begin{vmatrix} 2 & -1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & -1 \end{vmatrix}$

Solution Expanding the determinant along first row, we have

$$\begin{aligned} \Delta &= 2 \begin{vmatrix} 0 & 1 \\ 1 & -1 \end{vmatrix} - (-1) \begin{vmatrix} 1 & 1 \\ 1 & -1 \end{vmatrix} + 1 \begin{vmatrix} 1 & 0 \\ 1 & 1 \end{vmatrix} \\ &= 2 (0 - 1) + 1 (-1 - 1) + 1 (1 - 0) \\ &= -2 - 2 + 1 = -3 \end{aligned}$$

By interchanging rows and columns, we get

$$\begin{aligned} \Delta_1 &= \begin{vmatrix} 2 & 1 & 1 \\ -1 & 0 & 1 \\ 1 & 1 & -1 \end{vmatrix} \quad (\text{Expanding along first column}) \\ &= 2 \begin{vmatrix} 0 & 1 \\ 1 & -1 \end{vmatrix} - (-1) \begin{vmatrix} 1 & 1 \\ 1 & -1 \end{vmatrix} + 1 \begin{vmatrix} 1 & 1 \\ 0 & 1 \end{vmatrix} \\ &= 2 (0 - 1) + 1 (-1 - 1) + 1 (1 - 0) \\ &= -2 - 2 + 1 = -3 \end{aligned}$$

Clearly $\Delta = \Delta_1$

Hence, Property 1 is verified.

Property 2 If any two rows (or columns) of a determinant are interchanged, then sign of determinant changes.

Verification Let $\Delta = \begin{vmatrix} a_1 & a_2 & a_3 \\ b_1 & b_2 & b_3 \\ c_1 & c_2 & c_3 \end{vmatrix}$

Expanding along first row, we get

$$\Delta = a_1 (b_2 c_3 - b_3 c_2) - a_2 (b_1 c_3 - b_3 c_1) + a_3 (b_1 c_2 - b_2 c_1)$$

Interchanging first and third rows, the new determinant obtained is given by

$$\Delta_1 = \begin{vmatrix} c_1 & c_2 & c_3 \\ b_1 & b_2 & b_3 \\ a_1 & a_2 & a_3 \end{vmatrix}$$

Expanding along third row, we get

$$\begin{aligned} \Delta_1 &= a_1 (c_2 b_3 - b_2 c_3) - a_2 (c_1 b_3 - c_3 b_1) + a_3 (b_2 c_1 - b_1 c_2) \\ &= - [a_1 (b_2 c_3 - b_3 c_2) - a_2 (b_1 c_3 - b_3 c_1) + a_3 (b_1 c_2 - b_2 c_1)] \end{aligned}$$

Clearly $\Delta_1 = -\Delta$

Similarly, we can verify the result by interchanging any two columns.

 **Note** We can denote the interchange of rows by $R_i \leftrightarrow R_j$ and interchange of columns by $C_i \leftrightarrow C_j$.

Example 7 Verify property 2 for $\Delta = \begin{vmatrix} 2 & -3 & 4 \\ 3 & 0 & 5 \\ 1 & 4 & -2 \end{vmatrix}$.

Solution $\Delta = \begin{vmatrix} 2 & -3 & 4 \\ 3 & 0 & 5 \\ 1 & 4 & -2 \end{vmatrix} = -2$ (See Example 1)

Interchanging rows R_2 and R_3 i.e., $R_2 \leftrightarrow R_3$, we have

$$\Delta_1 = \begin{vmatrix} 2 & -3 & 4 \\ 1 & 4 & -2 \\ 3 & 0 & 5 \end{vmatrix}$$

Expanding the determinant Δ_1 along first row, we have

$$\begin{aligned} \Delta_1 &= 2 \begin{vmatrix} 4 & -2 \\ 0 & 5 \end{vmatrix} - (-3) \begin{vmatrix} 1 & -2 \\ 3 & 5 \end{vmatrix} + 4 \begin{vmatrix} 1 & 4 \\ 3 & 0 \end{vmatrix} \\ &= 2(20 - 0) + 3(5 + 6) + 4(0 - 12) \\ &= 20 + 15 - 48 = 2 \end{aligned}$$

Clearly $\Delta_1 = -\Delta$

Hence, Property 2 is verified.

Property 3 If any two rows (or columns) of a determinant are identical (all corresponding elements are same), then value of determinant is zero.

Proof If we interchange the identical rows (or columns) of the determinant Δ , then Δ does not change. However, by Property 2, it follows that Δ has changed its sign

Therefore $\Delta = -\Delta$

or $\Delta = 0$

Let us verify the above property by an example.

Example 8 Evaluate $\Delta = \begin{vmatrix} 1 & 2 & 1 \\ 2 & 2 & 1 \\ 1 & 2 & 1 \end{vmatrix}$

Solution Expanding along first row, we get

$$\begin{aligned} \Delta &= 1(2 \cdot 1 - 1 \cdot 1) - 2(2 \cdot 1 - 1 \cdot 1) + 1(2 \cdot 1 - 2 \cdot 1) \\ &= 0 - 2(1) + 1(0) = 0 - 2 = -2 \end{aligned}$$

Here R_1 and R_3 are identical.

Property 4 If each element of a row (or a column) of a determinant is multiplied by a constant k , then its value gets multiplied by k .

Verification Let $\Delta = \begin{vmatrix} a_1 & b_1 & c_1 \\ a_2 & b_2 & c_2 \\ a_3 & b_3 & c_3 \end{vmatrix}$

and Δ_1 be the determinant obtained by multiplying the elements of the first row by k . Then

$$\Delta_1 = \begin{vmatrix} k a_1 & k b_1 & k c_1 \\ a_2 & b_2 & c_2 \\ a_3 & b_3 & c_3 \end{vmatrix}$$

Expanding along first row, we get

$$\begin{aligned} \Delta_1 &= k a_1 (b_2 c_3 - b_3 c_2) - k b_1 (a_2 c_3 - c_2 a_3) + k c_1 (a_2 b_3 - b_2 a_3) \\ &= k [a_1 (b_2 c_3 - b_3 c_2) - b_1 (a_2 c_3 - c_2 a_3) + c_1 (a_2 b_3 - b_2 a_3)] \\ &= k \Delta \end{aligned}$$

∴ Hence
$$\begin{vmatrix} ka_1 & kb_1 & kc_1 \\ a_2 & b_2 & c_2 \\ a_3 & b_3 & c_3 \end{vmatrix} = k \begin{vmatrix} a_1 & b_1 & c_1 \\ a_2 & b_2 & c_2 \\ a_3 & b_3 & c_3 \end{vmatrix}$$

Remarks

- (i) By this property, we can take out any common factor from any one row or any one column of a given determinant.
- (ii) If corresponding elements of any two rows (or columns) of a determinant are proportional (in the same ratio), then its value is zero. For example

$$\Delta = \begin{vmatrix} a_1 & a_2 & a_3 \\ b_1 & b_2 & b_3 \\ ka_1 & ka_2 & ka_3 \end{vmatrix} = 0 \text{ (rows } R_1 \text{ and } R_2 \text{ are proportional)}$$

Example 9 Evaluate
$$\begin{vmatrix} 102 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{vmatrix}$$

Solution Note that
$$\begin{vmatrix} 102 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{vmatrix} = \begin{vmatrix} 102 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{vmatrix} = \begin{vmatrix} 102 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{vmatrix} = 0$$

(Using properties and)

Property 5 If some or all elements of a row or column of a determinant are expressed as sum of two (or more) terms, then the determinant can be expressed as sum of two (or more) determinants.

For example,
$$\begin{vmatrix} a_1 + \lambda_1 & a_2 + \lambda_2 & a_3 + \lambda_3 \\ b_1 & b_2 & b_3 \\ c_1 & c_2 & c_3 \end{vmatrix} = \begin{vmatrix} a_1 & a_2 & a_3 \\ b_1 & b_2 & b_3 \\ c_1 & c_2 & c_3 \end{vmatrix} + \begin{vmatrix} \lambda_1 & \lambda_2 & \lambda_3 \\ b_1 & b_2 & b_3 \\ c_1 & c_2 & c_3 \end{vmatrix}$$

Verification L.H.S. =
$$\begin{vmatrix} a_1 + \lambda_1 & a_2 + \lambda_2 & a_3 + \lambda_3 \\ b_1 & b_2 & b_3 \\ c_1 & c_2 & c_3 \end{vmatrix}$$

Expanding the determinants along the first row, we get

$$\begin{aligned} \Delta &= (a_1 + \lambda_1) (b_2 c_3 - c_2 b_3) - (a_2 + \lambda_2) (b_1 c_3 - b_3 c_1) \\ &\quad + (a_3 + \lambda_3) (b_1 c_2 - b_2 c_1) \\ &= a_1 (b_2 c_3 - c_2 b_3) - a_2 (b_1 c_3 - b_3 c_1) + a_3 (b_1 c_2 - b_2 c_1) \\ &\quad + \lambda_1 (b_2 c_3 - c_2 b_3) - \lambda_2 (b_1 c_3 - b_3 c_1) + \lambda_3 (b_1 c_2 - b_2 c_1) \end{aligned}$$

(by rearranging terms)

$$= \begin{vmatrix} a_1 & a_2 & a_3 \\ b_1 & b_2 & b_3 \\ c_1 & c_2 & c_3 \end{vmatrix} + \begin{vmatrix} \lambda_1 & \lambda_2 & \lambda_3 \\ b_1 & b_2 & b_3 \\ c_1 & c_2 & c_3 \end{vmatrix} = R. □. S.$$

Similarly, we may verify □ property □ for other rows or columns.

Example 10 Show that $\begin{vmatrix} a & b & c \\ a + 2x & b + 2y & c + 2z \\ x & y & z \end{vmatrix} = 0$

Solution We have $\begin{vmatrix} a & b & c \\ a + 2x & b + 2y & c + 2z \\ x & y & z \end{vmatrix} = \begin{vmatrix} a & b & c \\ a & b & c \\ x & y & z \end{vmatrix} + \begin{vmatrix} a & b & c \\ 2x & 2y & 2z \\ x & y & z \end{vmatrix}$

(by □ property □)

$= 0 + 0 = 0$ (□sing □ property □ and □ property □)

Property 6 If, to each element of any row or column of a determinant, the equimultiples of corresponding elements of other row (or column) are added, then value of determinant remains the same, i.e., the value of determinant remain same if we apply the operation $R_i \rightarrow R_i + kR_j$ or $\square_i \rightarrow \square_i + k\square_j$.

Verification

Let $\Delta = \begin{vmatrix} a_1 & a_2 & a_3 \\ b_1 & b_2 & b_3 \\ c_1 & c_2 & c_3 \end{vmatrix}$ and $\Delta_1 = \begin{vmatrix} a_1 + k c_1 & a_2 + k c_2 & a_3 + k c_3 \\ b_1 & b_2 & b_3 \\ c_1 & c_2 & c_3 \end{vmatrix}$,

where Δ_1 is obtained by the operation $R_1 \rightarrow R_1 + kR_3$.

Here, we have multiplied the elements of the third row (R_3) by a constant k and added them to the corresponding elements of the first row (R_1).

Symbolically, we write this operation as $R_1 \rightarrow R_1 + k R_3$

Now, again

$$\Delta_1 = \begin{vmatrix} a_1 & a_2 & a_\square \\ b_1 & b_2 & b_\square \\ c_1 & c_2 & c_\square \end{vmatrix} + \begin{vmatrix} kc_1 & kc_2 & kc_\square \\ b_1 & b_2 & b_\square \\ c_1 & c_2 & c_\square \end{vmatrix} \quad (\square \text{sing } \square \text{roperty } \square)$$

$$= \Delta + 0 \quad (\text{since } R_1 \text{ and } R_\square \text{ are proportional})$$

□ence $\Delta = \Delta_1$

Remarks

- (i) If Δ_1 is the determinant obtained by applying $R_i \rightarrow kR_i$ or $\square_i \rightarrow k\square_i$ to the determinant Δ , then $\Delta_1 = k\Delta$.
- (ii) If more than one operation like $R_i \rightarrow R_i + kR_j$ is done in one step, care should be taken to see that a row that is affected in one operation should not be used in another operation. A similar remark applies to column operations.

Example 11 □rove that $\begin{vmatrix} a & a+b & a+b+c \\ 2a & \square a+2b & \square a+\square b+2c \\ \square a & \square a+\square b & 10a+\square b+\square c \end{vmatrix} = a^\square$.

Solution Applying operations $R_2 \rightarrow R_2 - 2R_1$ and $R_\square \rightarrow R_\square - \square R_1$ to the given determinant Δ , we have

$$\Delta = \begin{vmatrix} a & a+b & a+b+c \\ 0 & a & 2a+b \\ 0 & \square a & \square a+\square b \end{vmatrix}$$

Now applying $R_\square \rightarrow R_\square - \square R_2$, we get

$$\Delta = \begin{vmatrix} a & a+b & a+b+c \\ 0 & a & 2a+b \\ 0 & 0 & a \end{vmatrix}$$

Expanding along \square_1 , we obtain

$$\Delta = a \begin{vmatrix} a & 2a+b \\ 0 & a \end{vmatrix} + 0 + 0$$

$$= a(a^2 - 0) = a(a^2) = a^\square$$

Example 12 Without expanding, prove that

$$\Delta = \begin{vmatrix} x+y & y+z & z+x \\ z & x & y \\ 1 & 1 & 1 \end{vmatrix} = 0$$

Solution Applying $R_1 \rightarrow R_1 + R_2$ to Δ , we get

$$\Delta = \begin{vmatrix} x+y+z & x+y+z & x+y+z \\ z & x & y \\ 1 & 1 & 1 \end{vmatrix}$$

Since the elements of R_1 and R_3 are proportional, $\Delta \equiv 0$.

Example 13 Evaluate

$$\Delta = \begin{vmatrix} 1 & a & bc \\ 1 & b & ca \\ 1 & c & ab \end{vmatrix}$$

Solution Applying $R_2 \rightarrow R_2 - R_1$ and $R_3 \rightarrow R_3 - R_1$, we get

$$\Delta = \begin{vmatrix} 1 & a & bc \\ 0 & b-a & c(a-b) \\ 0 & c-a & b(a-c) \end{vmatrix}$$

Taking factors $(b-a)$ and $(c-a)$ common from R_2 and R_3 respectively, we get

$$\begin{aligned} \Delta &= (b-a)(c-a) \begin{vmatrix} 1 & a & bc \\ 0 & 1 & -c \\ 0 & 1 & -b \end{vmatrix} \\ &= (b-a)(c-a)[(-b+c)] \text{ (Expanding along first column)} \\ &= (a-b)(b-c)(c-a) \end{aligned}$$

Example 14 Prove that $\begin{vmatrix} b+c & a & a \\ b & c+a & b \\ c & c & a+b \end{vmatrix} = abc$

Solution Let $\Delta = \begin{vmatrix} b+c & a & a \\ b & c+a & b \\ c & c & a+b \end{vmatrix}$

Applying $R_1 \rightarrow R_1 - R_2 - R_3$ to Δ , we get

$$\Delta = \begin{vmatrix} 0 & -2c & -2b \\ b & c+a & b \\ c & c & a+b \end{vmatrix}$$

Expanding along R_1 , we obtain

$$\begin{aligned} \Delta &= 0 \begin{vmatrix} c+a & b \\ c & a+b \end{vmatrix} - (-2c) \begin{vmatrix} b & b \\ c & a+b \end{vmatrix} + (-2b) \begin{vmatrix} b & c+a \\ c & c \end{vmatrix} \\ &= 2c(a+b-bc) - 2b(bc-c^2-ac) \\ &= 2abc + 2cb^2 - 2bc^2 - 2b^2c + 2bc^2 + 2abc \\ &= 4abc \end{aligned}$$

Example 15 If x, y, z are different and $\Delta = \begin{vmatrix} x & x^2 & 1+x \\ y & y^2 & 1+y \\ z & z^2 & 1+z \end{vmatrix} = 0$, then

show that $1 + xyz = 0$

Solution We have

$$\begin{aligned} \Delta &= \begin{vmatrix} x & x^2 & 1+x \\ y & y^2 & 1+y \\ z & z^2 & 1+z \end{vmatrix} \\ &= \begin{vmatrix} x & x^2 & 1 \\ y & y^2 & 1 \\ z & z^2 & 1 \end{vmatrix} + \begin{vmatrix} x & x^2 & x \\ y & y^2 & y \\ z & z^2 & z \end{vmatrix} \quad (\text{sing. property}) \\ &= (-1)^2 \begin{vmatrix} 1 & x & x^2 \\ 1 & y & y^2 \\ 1 & z & z^2 \end{vmatrix} + xyz \begin{vmatrix} 1 & x & x^2 \\ 1 & y & y^2 \\ 1 & z & z^2 \end{vmatrix} \quad (\text{sing. } \begin{vmatrix} \square_1 & \square_2 & \square_3 \\ \square_1 & \square_2 & \square_3 \\ \square_1 & \square_2 & \square_3 \end{vmatrix} \leftrightarrow \begin{vmatrix} \square_1 & \square_2 & \square_3 \\ \square_1 & \square_2 & \square_3 \\ \square_1 & \square_2 & \square_3 \end{vmatrix}) \\ &= \begin{vmatrix} 1 & x & x^2 \\ 1 & y & y^2 \\ 1 & z & z^2 \end{vmatrix} (1+xyz) \end{aligned}$$

$$= (1+xyz) \begin{vmatrix} 1 & x & x^2 \\ 0 & y-x & y^2-x^2 \\ 0 & z-x & z^2-x^2 \end{vmatrix} \quad (\text{Using } R_2 \rightarrow R_2 - R_1 \text{ and } R_3 \rightarrow R_3 - R_1)$$

Taking out common factor $(y-x)$ from R_2 and $(z-x)$ from R_3 , we get

$$\Delta = (1+xyz)(y-x)(z-x) \begin{vmatrix} 1 & x & x^2 \\ 0 & 1 & y+x \\ 0 & 1 & z+x \end{vmatrix}$$

$$= (1+xyz)(y-x)(z-x)(z-y) \quad (\text{on expanding along } R_1)$$

Since $\Delta = 0$ and x, y, z are all different, i.e., $x-y \neq 0$, $y-z \neq 0$, $z-x \neq 0$, we get $1+xyz = 0$

Example 16 Show that

$$\begin{vmatrix} 1+a & 1 & 1 \\ 1 & 1+b & 1 \\ 1 & 1 & 1+c \end{vmatrix} = abc \left(1 + \frac{1}{a} + \frac{1}{b} + \frac{1}{c} \right) = abc + bc + ca + ab$$

Solution Taking out factors a, b, c common from R_1, R_2 and R_3 , we get

$$\therefore \Delta = abc \begin{vmatrix} \frac{1}{a}+1 & \frac{1}{a} & \frac{1}{a} \\ \frac{1}{b} & \frac{1}{b}+1 & \frac{1}{b} \\ \frac{1}{c} & \frac{1}{c} & \frac{1}{c}+1 \end{vmatrix}$$

Applying $R_1 \rightarrow R_1 + R_2 + R_3$, we have

$$\Delta = abc \begin{vmatrix} 1 + \frac{1}{a} + \frac{1}{b} + \frac{1}{c} & 1 + \frac{1}{a} + \frac{1}{b} + \frac{1}{c} & 1 + \frac{1}{a} + \frac{1}{b} + \frac{1}{c} \\ \frac{1}{b} & \frac{1}{b}+1 & \frac{1}{b} \\ \frac{1}{c} & \frac{1}{c} & \frac{1}{c}+1 \end{vmatrix}$$

$$= abc \left(1 + \frac{1}{a} + \frac{1}{b} + \frac{1}{c} \right) \begin{vmatrix} 1 & 1 & 1 \\ \frac{1}{b} & \frac{1}{b} + 1 & \frac{1}{b} \\ \frac{1}{c} & \frac{1}{c} & \frac{1}{c} + 1 \end{vmatrix}$$

Now applying $\square_2 \rightarrow \square_2 - \square_1$, $\square_3 \rightarrow \square_3 - \square_1$, we get

$$\begin{aligned} \Delta &= abc \left(1 + \frac{1}{a} + \frac{1}{b} + \frac{1}{c} \right) \begin{vmatrix} 1 & 0 & 0 \\ \frac{1}{b} & 1 & 0 \\ \frac{1}{c} & 0 & 1 \end{vmatrix} \\ &= abc \left(1 + \frac{1}{a} + \frac{1}{b} + \frac{1}{c} \right) [1(1-0)] \\ &= abc \left(1 + \frac{1}{a} + \frac{1}{b} + \frac{1}{c} \right) = abc + bc + ca + ab = \text{R.}\square.\text{S.} \end{aligned}$$

 **Note** Alternately try by applying $\square_1 \rightarrow \square_1 - \square_2$ and $\square_3 \rightarrow \square_3 - \square_2$, then apply $\square_1 \rightarrow \square_1 - a \square_3$

EXERCISE 4.2

Using the property of determinants and without expanding in Exercises 1 to 5, prove that

1. $\begin{vmatrix} x & a & x+a \\ y & b & y+b \\ z & c & z+c \end{vmatrix} = 0$

2. $\begin{vmatrix} a-b & b-c & c-a \\ b-c & c-a & a-b \\ c-a & a-b & b-c \end{vmatrix} = 0$

3. $\begin{vmatrix} 2 & \square & \square \\ \square & \square & \square \\ \square & \square & \square \end{vmatrix} = 0$

4. $\begin{vmatrix} 1 & bc & a(b+c) \\ 1 & ca & b(c+a) \\ 1 & ab & c(a+b) \end{vmatrix} = 0$

5. $\begin{vmatrix} b+c & q+r & y+z \\ c+a & r+p & z+x \\ a+b & p+q & x+y \end{vmatrix} = 2 \begin{vmatrix} a & p & x \\ b & q & y \\ c & r & z \end{vmatrix}$

$$6. \begin{vmatrix} 0 & a & -b \\ -a & 0 & -c \\ b & c & 0 \end{vmatrix} = 0$$

$$7. \begin{vmatrix} -a^2 & ab & ac \\ ba & -b^2 & bc \\ ca & cb & -c^2 \end{vmatrix} = -a^2 b^2 c^2$$

By using properties of determinants, in Exercises 8 to 11 show that

$$8. (i) \begin{vmatrix} 1 & a & a^2 \\ 1 & b & b^2 \\ 1 & c & c^2 \end{vmatrix} = (a-b)(b-c)(c-a)$$

$$(ii) \begin{vmatrix} 1 & 1 & 1 \\ a & b & c \\ a^2 & b^2 & c^2 \end{vmatrix} = (a-b)(b-c)(c-a)(a+b+c)$$

$$9. \begin{vmatrix} x & x^2 & yz \\ y & y^2 & zx \\ z & z^2 & xy \end{vmatrix} = (x-y)(y-z)(z-x)(xy+yz+zx)$$

$$10. (i) \begin{vmatrix} x+k & 2x & 2x \\ 2x & x+k & 2x \\ 2x & 2x & x+k \end{vmatrix} = (x+k)(x-k)^2$$

$$(ii) \begin{vmatrix} y+k & y & y \\ y & y+k & y \\ y & y & y+k \end{vmatrix} = k^2(y+k)$$

$$11. (i) \begin{vmatrix} a-b-c & 2a & 2a \\ 2b & b-c-a & 2b \\ 2c & 2c & c-a-b \end{vmatrix} = (a+b+c)^3$$

$$(ii) \begin{vmatrix} x+y+2z & x & y \\ z & y+z+2x & y \\ z & x & z+x+2y \end{vmatrix} = 2(x+y+z)^3$$

$$12. \begin{vmatrix} 1 & x & x^2 \\ x^2 & 1 & x \\ x & x^2 & 1 \end{vmatrix} = (1-x)^2$$

$$13. \begin{vmatrix} 1+a^2-b^2 & 2ab & -2b \\ 2ab & 1-a^2+b^2 & 2a \\ 2b & -2a & 1-a^2-b^2 \end{vmatrix} = (1+a^2+b^2)^2$$

$$14. \begin{vmatrix} a^2+1 & ab & ac \\ ab & b^2+1 & bc \\ ca & cb & c^2+1 \end{vmatrix} = 1+a^2+b^2+c^2$$

Choose the correct answer in Exercises 15 and 16

15. Let A be a square matrix of order n , then kA is equal to
 (A) kA (B) k^2A (C) k^nA (D) k^nA

16. Which of the following is correct
 (A) Determinant is a square matrix.
 (B) Determinant is a number associated to a matrix.
 (C) Determinant is a number associated to a square matrix.
 (D) None of these

4.4 Area of a Triangle

In earlier classes, we have studied that the area of a triangle whose vertices are (x_1, y_1) , (x_2, y_2) and (x_3, y_3) , is given by the expression $\frac{1}{2}[x_1(y_2-y_3) + x_2(y_3-y_1) + x_3(y_1-y_2)]$. Now this expression can be written in the form of a determinant as

$$\Delta = \frac{1}{2} \begin{vmatrix} x_1 & y_1 & 1 \\ x_2 & y_2 & 1 \\ x_3 & y_3 & 1 \end{vmatrix} \quad \dots (1)$$

Remarks

- (i) Since area is a positive quantity, we always take the absolute value of the determinant in (1).

- (ii) If area is given, use both positive and negative values of the determinant for calculation.
- (iii) The area of the triangle formed by three collinear points is zero.

Example 17 Find the area of the triangle whose vertices are $(1, 2)$, $(-1, 2)$ and $(1, 1)$.

Solution The area of triangle is given by

$$\begin{aligned}\Delta &= \frac{1}{2} \begin{vmatrix} 1 & 2 & 1 \\ -1 & 2 & 1 \\ 1 & 1 & 1 \end{vmatrix} \\ &= \frac{1}{2} [1(2-1) - 1(-1-1) + 1(-1-10)] \\ &= \frac{1}{2} (1+2-10) = \frac{7}{2}\end{aligned}$$

Example 18 Find the equation of the line joining $A(1, 2)$ and $B(0, 0)$ using determinants and find k if $D(k, 0)$ is a point such that area of triangle ABD is 4 sq units.

Solution Let $P(x, y)$ be any point on AB . Then, area of triangle ABP is zero (Why?). So

$$\frac{1}{2} \begin{vmatrix} 0 & 0 & 1 \\ 1 & 2 & 1 \\ x & y & 1 \end{vmatrix} = 0$$

This gives $\frac{1}{2}(y - 2x) = 0$ or $y = 2x$,

which is the equation of required line AB .

Also, since the area of the triangle ABD is 4 sq. units, we have

$$\frac{1}{2} \begin{vmatrix} 1 & 2 & 1 \\ 0 & 0 & 1 \\ k & 0 & 1 \end{vmatrix} = 4$$

This gives, $\frac{-k}{2} = \pm 4$, i.e., $k = \mp 8$.

EXERCISE 4.3

1. Find area of the triangle with vertices at the point given in each of the following
- (i) $(1, 0)$, $(2, 0)$, $(2, 2)$ (ii) $(2, 2)$, $(1, 1)$, $(10, 2)$
- (iii) $(-2, -1)$, $(2, 2)$, $(-1, -1)$

2. Show that points $A(a, b + c), B(b, c + a), C(c, a + b)$ are collinear.
3. Find values of k if area of triangle is λ sq. units and vertices are
 - (i) $(k, 0), (\lambda, 0), (0, 2)$ (ii) $(-2, 0), (0, \lambda), (0, k)$
4. (i) Find equation of line joining $(1, 2)$ and (λ, λ) using determinants.
 (ii) Find equation of line joining $(\lambda, 1)$ and (λ, λ) using determinants.
5. If area of triangle is λ sq units with vertices $(2, -\lambda), (\lambda, \lambda)$ and (k, λ) . Then k is
 (A) 12 (B) $-\lambda$ (C) $-\lambda, -2$ (D) $12, -2$

4.5 Minors and Cofactors

In this section, we will learn to write the expansion of a determinant in compact form using minors and cofactors.

Definition 1 Minor of an element a_{ij} of a determinant is the determinant obtained by deleting its i th row and j th column in which element a_{ij} lies. Minor of an element a_{ij} is denoted by M_{ij} .

Remark Minor of an element of a determinant of order $n(n \geq 2)$ is a determinant of order $n - 1$.

Example 19 Find the minor of element λ in the determinant $\Delta = \begin{vmatrix} 1 & 2 & \lambda \\ \lambda & \lambda & \lambda \\ \lambda & \lambda & \lambda \end{vmatrix}$

Solution Since λ lies in the second row and third column, its minor M_{23} is given by

$$M_{23} = \begin{vmatrix} 1 & 2 \\ \lambda & \lambda \end{vmatrix} = \lambda - 2\lambda = -\lambda \text{ (obtained by deleting } R_2 \text{ and } C_3 \text{ in } \Delta).$$

Definition 2 Cofactor of an element a_{ij} , denoted by A_{ij} is defined by

$$A_{ij} = (-1)^{i+j} M_{ij}, \text{ where } M_{ij} \text{ is minor of } a_{ij}.$$

Example 20 Find minors and cofactors of all the elements of the determinant $\begin{vmatrix} 1 & -2 \\ \lambda & \lambda \end{vmatrix}$

Solution Minor of the element a_{ij} is M_{ij}
 Here $a_{11} = 1$. So $M_{11} = \text{Minor of } a_{11} = \lambda$
 $M_{12} = \text{Minor of the element } a_{12} = -2$
 $M_{21} = \text{Minor of the element } a_{21} = -2$

M_{22} = Minor of the element $a_{22} = 1$

Now, cofactor of a_{ij} is A_{ij} . So

$$A_{11} = (-1)^{1+1} M_{11} = (-1)^2 (1) = 1$$

$$A_{12} = (-1)^{1+2} M_{12} = (-1)^3 (1) = -1$$

$$A_{21} = (-1)^{2+1} M_{21} = (-1)^3 (-2) = 2$$

$$A_{22} = (-1)^{2+2} M_{22} = (-1)^4 (1) = 1$$

Example 21 Find minors and cofactors of the elements a_{11} , a_{21} in the determinant

$$\Delta = \begin{vmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{vmatrix}$$

Solution By definition of minors and cofactors, we have

$$\text{Minor of } a_{11} = M_{11} = \begin{vmatrix} a_{22} & a_{23} \\ a_{32} & a_{33} \end{vmatrix} = a_{22} a_{33} - a_{23} a_{32}$$

$$\text{Cofactor of } a_{11} = A_{11} = (-1)^{1+1} M_{11} = a_{22} a_{33} - a_{23} a_{32}$$

$$\text{Minor of } a_{21} = M_{21} = \begin{vmatrix} a_{12} & a_{13} \\ a_{32} & a_{33} \end{vmatrix} = a_{12} a_{33} - a_{13} a_{32}$$

$$\text{Cofactor of } a_{21} = A_{21} = (-1)^{2+1} M_{21} = (-1) (a_{12} a_{33} - a_{13} a_{32}) = -a_{12} a_{33} + a_{13} a_{32}$$

Remark Expanding the determinant Δ , in Example 21, along R_1 , we have

$$\Delta = (-1)^{1+1} a_{11} \begin{vmatrix} a_{22} & a_{23} \\ a_{32} & a_{33} \end{vmatrix} + (-1)^{1+2} a_{12} \begin{vmatrix} a_{21} & a_{23} \\ a_{31} & a_{33} \end{vmatrix} + (-1)^{1+3} a_{13} \begin{vmatrix} a_{21} & a_{22} \\ a_{31} & a_{32} \end{vmatrix}$$

$$= a_{11} A_{11} + a_{12} A_{12} + a_{13} A_{13}, \text{ where } A_{ij} \text{ is cofactor of } a_{ij}$$

$$= \text{sum of product of elements of } R_1 \text{ with their corresponding cofactors}$$

Similarly, Δ can be calculated by other five ways of expansion that is along R_2 , R_3 , C_1 , C_2 and C_3 .

Hence Δ = sum of the product of elements of any row (or column) with their corresponding cofactors.

 **Note** If elements of a row (or column) are multiplied with cofactors of any other row (or column), then their sum is zero. For example,

$$\begin{aligned}
 \Delta &= a_{11} A_{21} + a_{12} A_{22} + a_{13} A_{23} \\
 &= a_{11} (-1)^{1+1} \begin{vmatrix} a_{12} & a_{13} \\ a_{22} & a_{23} \end{vmatrix} + a_{12} (-1)^{1+2} \begin{vmatrix} a_{11} & a_{13} \\ a_{21} & a_{23} \end{vmatrix} + a_{13} (-1)^{1+3} \begin{vmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{vmatrix} \\
 &= \begin{vmatrix} a_{11} & a_{12} & a_{13} \\ a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \end{vmatrix} = 0 \text{ (since } R_1 \text{ and } R_2 \text{ are identical)}
 \end{aligned}$$

Similarly, we can try for other rows and columns.

Example 22 Find minors and cofactors of the elements of the determinant

$$\begin{vmatrix} 2 & -1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & -1 \end{vmatrix} \text{ and verify that } a_{11} A_{11} + a_{12} A_{12} + a_{13} A_{13} = 0$$

Solution We have $M_{11} = \begin{vmatrix} 0 & 1 \\ 1 & -1 \end{vmatrix} = 0 - 1 = -1 = -1 A_{11} = (-1)^{1+1} (-1) = -1$

$$M_{12} = \begin{vmatrix} 1 & 1 \\ 1 & -1 \end{vmatrix} = -1 - 1 = -2 = -2 A_{12} = (-1)^{1+2} (-2) = 2$$

$$M_{13} = \begin{vmatrix} 1 & 0 \\ 1 & 1 \end{vmatrix} = 1 - 0 = 1 = 1 A_{13} = (-1)^{1+3} (1) = 1$$

$$M_{21} = \begin{vmatrix} -1 & 1 \\ 1 & -1 \end{vmatrix} = 1 - 1 = 0 = 0 A_{21} = (-1)^{2+1} (0) = 0$$

$$M_{22} = \begin{vmatrix} 2 & 1 \\ 1 & -1 \end{vmatrix} = -2 - 1 = -3 = -3 A_{22} = (-1)^{2+2} (-3) = -3$$

$$M_{23} = \begin{vmatrix} 2 & -1 \\ 1 & 1 \end{vmatrix} = 2 + 1 = 3 = 3 A_{23} = (-1)^{2+3} (3) = -3$$

$$M_{31} = \begin{vmatrix} -1 & 1 \\ 0 & 1 \end{vmatrix} = -1 - 0 = -1 = -1 A_{31} = (-1)^{3+1} (-1) = 1$$

$$M_{12} = \begin{vmatrix} 2 & 1 \\ 1 & 1 \end{vmatrix} = 2 - 1 = 1 \quad A_{12} = (-1)^{1+2}(-1) = 1$$

and $M_{11} = \begin{vmatrix} 2 & -1 \\ 1 & 0 \end{vmatrix} = 0 + 1 = 1 \quad A_{11} = (-1)^{1+1}(1) = 1$

Now $a_{11} = 2, a_{12} = -1, a_{13} = 1, A_{11} = -1, A_{12} = 2, A_{13} = 1$

So $a_{11}A_{11} + a_{12}A_{12} + a_{13}A_{13}$
 $= 2(-1) + (-1)(2) + 1(1) = -2 - 2 + 1 = 0$

EXERCISE 4.4

Write Minors and Cofactors of the elements of following determinants

1. (i) $\begin{vmatrix} 2 & -1 \\ 0 & 1 \end{vmatrix}$ (ii) $\begin{vmatrix} a & c \\ b & d \end{vmatrix}$

2. (i) $\begin{vmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{vmatrix}$ (ii) $\begin{vmatrix} 1 & 0 & 1 \\ 1 & 1 & -1 \\ 0 & 1 & 2 \end{vmatrix}$

3. Cofactors of elements of second row, evaluate $\Delta = \begin{vmatrix} 1 & 1 & 1 \\ 2 & 0 & 1 \\ 1 & 2 & 1 \end{vmatrix}$.

4. Cofactors of elements of third column, evaluate $\Delta = \begin{vmatrix} 1 & x & yz \\ 1 & y & zx \\ 1 & z & xy \end{vmatrix}$.

5. If $\Delta = \begin{vmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{vmatrix}$ and A_{ij} is Cofactors of a_{ij} , then value of Δ is given by

(A) $a_{11}A_{11} + a_{12}A_{12} + a_{13}A_{13}$ (B) $a_{11}A_{11} + a_{12}A_{21} + a_{13}A_{31}$

(C) $a_{21}A_{11} + a_{22}A_{12} + a_{23}A_{13}$ (D) $a_{11}A_{11} + a_{21}A_{21} + a_{31}A_{31}$

4.6 Adjoint and Inverse of a Matrix

In the previous chapter, we have studied inverse of a matrix. In this section, we shall discuss the condition for existence of inverse of a matrix.

To find inverse of a matrix A, i.e., A^{-1} we shall first define adjoint of a matrix.

4.6.1 Adjoint of a matrix

Definition 3 The adjoint of a square matrix $A = [a_{ij}]_{n \times n}$ is defined as the transpose of the matrix $[A_{ij}]_{n \times n}$, where A_{ij} is the cofactor of the element a_{ij} . Adjoint of the matrix A is denoted by $adj A$.

Let
$$A = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}$$

Then $adj A = \text{Transpose of } \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{21} & A_{31} \\ A_{12} & A_{22} & A_{32} \\ A_{13} & A_{23} & A_{33} \end{bmatrix}$

Example 23 Find $adj A$ for $A = \begin{bmatrix} 2 & 3 \\ 1 & 4 \end{bmatrix}$

Solution We have $A_{11} = 4, A_{12} = -1, A_{21} = -3, A_{22} = 2$

Hence $adj A = \begin{bmatrix} A_{11} & A_{21} \\ A_{12} & A_{22} \end{bmatrix} = \begin{bmatrix} 4 & -3 \\ -1 & 2 \end{bmatrix}$

Remark For a square matrix of order 2, given by

$$A = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}$$

The $adj A$ can also be obtained by interchanging a_{11} and a_{22} and by changing signs of a_{12} and a_{21} , i.e.,

$$adj A = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} = \begin{bmatrix} a_{22} & -a_{12} \\ -a_{21} & a_{11} \end{bmatrix}$$

Change sign Interchange

We state the following theorem without proof.

Theorem 1 If A be any given square matrix of order n , then

$$A(adj A) = (adj A) A = |A|I,$$

where I is the identity matrix of order n

Verification

$$\text{Let } A = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}, \text{ then } \text{adj } A = \begin{bmatrix} A_{11} & A_{21} & A_{31} \\ A_{12} & A_{22} & A_{32} \\ A_{13} & A_{23} & A_{33} \end{bmatrix}$$

Since sum of product of elements of a row (or a column) with corresponding cofactors is equal to $|A|$ and otherwise zero, we have

$$A (\text{adj } A) = \begin{bmatrix} |A| & 0 & 0 \\ 0 & |A| & 0 \\ 0 & 0 & |A| \end{bmatrix} = |A| \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} = |A| I$$

Similarly, we can show $(\text{adj } A) A = |A| I$

$$\text{Hence } A (\text{adj } A) = (\text{adj } A) A = |A| I$$

Definition 4 A square matrix A is said to be singular if $|A| = 0$.

For example, the determinant of matrix $A = \begin{bmatrix} 1 & 2 \\ 1 & 1 \end{bmatrix}$ is zero

Hence A is a singular matrix.

Definition 5 A square matrix A is said to be non-singular if $|A| \neq 0$

Let $A = \begin{bmatrix} 1 & 2 \\ 1 & 1 \end{bmatrix}$. Then $|A| = \begin{vmatrix} 1 & 2 \\ 1 & 1 \end{vmatrix} = 1 - 2 = -1 \neq 0$.

Hence A is a nonsingular matrix

We state the following theorems without proof.

Theorem 2 If A and B are nonsingular matrices of the same order, then AB and BA are also nonsingular matrices of the same order.

Theorem 3 The determinant of the product of matrices is equal to product of their respective determinants, that is, $|AB| = |A| |B|$, where A and B are square matrices of the same order

Remark We know that $(\text{adj } A) A = |A| I = \begin{bmatrix} |A| & 0 & 0 \\ 0 & |A| & 0 \\ 0 & 0 & |A| \end{bmatrix}$

Writing determinants of matrices on both sides, we have

$$|(adj A)A| = \begin{vmatrix} |A| & 0 & 0 \\ 0 & |A| & 0 \\ 0 & 0 & |A| \end{vmatrix}$$

i.e. $(adj A)A = |A| \begin{vmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{vmatrix}$ (Why?)

i.e. $(adj A)A = |A| I$

i.e. $(adj A) = |A|^{-1} A$

In general, if A is a square matrix of order n , then $adj(A) = |A|^{-1} A$.

Theorem 4 A square matrix A is invertible if and only if A is nonsingular matrix.

Proof Let A be invertible matrix of order n and I be the identity matrix of order n .

Then, there exists a square matrix X of order n such that $AX = XA = I$

Now $AX = I$. So $|AX| = |I|$ or $|A| |X| = 1$ (since $|I|=1, |AX|=|A||X|$)

This gives $|A| \neq 0$. Hence A is nonsingular.

Conversely, let A be nonsingular. Then $|A| \neq 0$

Now $A(adj A) = (adj A)A = |A|I$ (Theorem 1)

or $A \left(\frac{1}{|A|} adj A \right) = \left(\frac{1}{|A|} adj A \right) A = I$

or $AX = XA = I$, where $X = \frac{1}{|A|} adj A$

Thus A is invertible and $A^{-1} = \frac{1}{|A|} adj A$

Example 24 If $A = \begin{bmatrix} 1 & a & b \\ 1 & a & c \\ 1 & a & d \end{bmatrix}$, then verify that $A adj A = |A| I$. Also find A^{-1} .

Solution We have $|A| = 1(1 \cdot d - c) - a(d - c) + a(c - d) = 1 \neq 0$

Now $A_{11} = 1, A_{12} = -1, A_{13} = -1, A_{21} = -1, A_{22} = 1, A_{23} = 0, A_{31} = -1, A_{32} = 0, A_{33} = 1$

Therefore
$$\text{adj } A = \begin{bmatrix} 1 & -1 & -1 \\ -1 & 1 & 0 \\ -1 & 0 & 1 \end{bmatrix}$$

Now
$$A (\text{adj } A) = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} 1 & -1 & -1 \\ -1 & 1 & 0 \\ -1 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} 1-1-1 & -1+1+0 & -1+0+1 \\ 1-1-1 & -1+1+0 & -1+0+1 \\ 1-1-1 & -1+1+0 & -1+0+1 \end{bmatrix}$$

$$= \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} = (1) \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} = |A| \cdot I$$

Also
$$A^{-1} = \frac{1}{|A|} \text{adj } A = \frac{1}{1} \begin{bmatrix} 1 & -1 & -1 \\ -1 & 1 & 0 \\ -1 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & -1 & -1 \\ -1 & 1 & 0 \\ -1 & 0 & 1 \end{bmatrix}$$

Example 25 If $A = \begin{bmatrix} 2 & 1 \\ 1 & -1 \end{bmatrix}$ and $B = \begin{bmatrix} 1 & -2 \\ -1 & 1 \end{bmatrix}$, then verify that $(AB)^{-1} = B^{-1}A^{-1}$.

Solution We have $AB = \begin{bmatrix} 2 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} 1 & -2 \\ -1 & 1 \end{bmatrix} = \begin{bmatrix} -1 & 1 \\ 1 & -1 \end{bmatrix}$

Since, $|AB| = -11 \neq 0$, $(AB)^{-1}$ exists and is given by

$$(AB)^{-1} = \frac{1}{|AB|} \text{adj } (AB) = -\frac{1}{11} \begin{bmatrix} -1 & -1 \\ -1 & -1 \end{bmatrix} = \frac{1}{11} \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}$$

Further, $|A| = -11 \neq 0$ and $|B| = 1 \neq 0$. Therefore, A^{-1} and B^{-1} both exist and are given by

$$A^{-1} = -\frac{1}{11} \begin{bmatrix} -1 & -1 \\ -1 & -1 \end{bmatrix}, B^{-1} = \begin{bmatrix} 1 & 2 \\ 1 & 1 \end{bmatrix}$$

$$\text{Therefore } \begin{bmatrix} 1 & 2 \\ 1 & 1 \end{bmatrix}^{-1} = -\frac{1}{11} \begin{bmatrix} 1 & 2 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} -1 & -1 \\ -1 & 2 \end{bmatrix} = -\frac{1}{11} \begin{bmatrix} -1 & -1 \\ -1 & -1 \end{bmatrix} = \frac{1}{11} \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}$$

$$\text{Hence } (A^{-1})^{-1} = A$$

Example 26 Show that the matrix $A = \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix}$ satisfies the equation $A^2 - \lambda A + I = 0$, where I is 2×2 identity matrix and 0 is 2×2 zero matrix. Using this equation, find A^{-1} .

Solution We have $A^2 = A \cdot A = \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} = \begin{bmatrix} 5 & 4 \\ 4 & 5 \end{bmatrix}$

$$\text{Hence } A^2 - \lambda A + I = \begin{bmatrix} 5 & 4 \\ 4 & 5 \end{bmatrix} - \lambda \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} = 0$$

$$\text{Now } A^2 - \lambda A + I = 0$$

$$\text{Therefore } A^2 - \lambda A = -I$$

$$\text{or } A(A - \lambda I) = -I \quad (\text{Post multiplying by } A^{-1} \text{ because } \det A \neq 0)$$

$$\text{or } A(A - \lambda I) = -I$$

$$\text{or } AI - \lambda I = -A^{-1}$$

$$\text{or } A^{-1} = I - \lambda A = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} - \lambda \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} = \begin{bmatrix} 1 - 2\lambda & -\lambda \\ -\lambda & 1 - 2\lambda \end{bmatrix}$$

$$\text{Hence } A^{-1} = \begin{bmatrix} 1 - 2\lambda & -\lambda \\ -\lambda & 1 - 2\lambda \end{bmatrix}$$

EXERCISE 4.5

Find adjoint of each of the matrices in Exercises 1 and 2.

$$1. \begin{bmatrix} 1 & 2 \\ 1 & 1 \end{bmatrix} \qquad 2. \begin{bmatrix} 1 & -1 & 2 \\ 2 & 1 & 1 \\ -2 & 0 & 1 \end{bmatrix}$$

Verify $A(\text{adj } A) = (\text{adj } A)A = |A|I$ in Exercises 1 and 2.

$$3. \begin{bmatrix} 2 & 1 \\ -1 & -1 \end{bmatrix} \qquad 4. \begin{bmatrix} 1 & -1 & 2 \\ 1 & 0 & 1 \\ 1 & 0 & 1 \end{bmatrix}$$

Find the inverse of each of the matrices (if it exists) given in Exercises 5 to 11.

5. $\begin{bmatrix} 2 & -2 \\ \square & \square \end{bmatrix}$

6. $\begin{bmatrix} -1 & \square \\ -\square & 2 \end{bmatrix}$

7. $\begin{bmatrix} 1 & 2 & \square \\ 0 & 2 & \square \\ 0 & 0 & \square \end{bmatrix}$

8. $\begin{bmatrix} 1 & 0 & 0 \\ \square & \square & 0 \\ \square & 2 & -1 \end{bmatrix}$

9. $\begin{bmatrix} 2 & 1 & \square \\ \square & -1 & 0 \\ -\square & 2 & 1 \end{bmatrix}$

10. $\begin{bmatrix} 1 & -1 & 2 \\ 0 & 2 & -\square \\ \square & -2 & \square \end{bmatrix}$

11. $\begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \alpha & \sin \alpha \\ 0 & \sin \alpha & -\cos \alpha \end{bmatrix}$

12. Let $A = \begin{bmatrix} \square & \square \\ 2 & \square \end{bmatrix}$ and $B = \begin{bmatrix} \square & \square \\ \square & \square \end{bmatrix}$. Verify that $(AB)^{-1} = B^{-1}A^{-1}$.

13. If $A = \begin{bmatrix} \square & 1 \\ -1 & 2 \end{bmatrix}$, show that $A^2 - \square A + \square I = \square$. Hence find A^{-1} .

14. For the matrix $A = \begin{bmatrix} \square & 2 \\ 1 & 1 \end{bmatrix}$, find the numbers a and b such that $A^2 + aA + bI = \square$.

15. For the matrix $A = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 2 & -\square \\ 2 & -1 & \square \end{bmatrix}$

Show that $A^3 - \square A^2 + \square A + 11I = \square$. Hence, find A^{-1} .

16. If $A = \begin{bmatrix} 2 & -1 & 1 \\ -1 & 2 & -1 \\ 1 & -1 & 2 \end{bmatrix}$

Verify that $A^3 - \square A^2 + \square A - \square I = \square$ and hence find A^{-1} .

17. Let A be a nonsingular square matrix of order $n \times n$. Then $\text{adj } A$ is equal to

(A) $\square A$ (B) $\square A^2$ (C) $\square A^3$ (D) $\square \square A$

18. If A is an invertible matrix of order 2, then $\det(A^{-1})$ is equal to

(A) $\det(A)$ (B) $\frac{1}{\det(A)}$ (C) 1 (D) 0

4.7 Applications of Determinants and Matrices

In this section, we shall discuss application of determinants and matrices for solving the system of linear equations in two or three variables and for checking the consistency of the system of linear equations.

Consistent system A system of equations is said to be *consistent* if its solution (one or more) exists.

Inconsistent system A system of equations is said to be *inconsistent* if its solution does not exist.

 **Note** In this chapter, we restrict ourselves to the system of linear equations having unique solutions only.

4.7.1 Solution of system of linear equations using inverse of a matrix

Let us express the system of linear equations as matrix equations and solve them using inverse of the coefficient matrix.

Consider the system of equations

$$\begin{aligned} a_1 x + b_1 y + c_1 z &= d_1 \\ a_2 x + b_2 y + c_2 z &= d_2 \\ a_n x + b_n y + c_n z &= d_n \end{aligned}$$

Let $A = \begin{bmatrix} a_1 & b_1 & c_1 \\ a_2 & b_2 & c_2 \\ a_n & b_n & c_n \end{bmatrix}$, $X = \begin{bmatrix} x \\ y \\ z \end{bmatrix}$ and $D = \begin{bmatrix} d_1 \\ d_2 \\ d_n \end{bmatrix}$

Then, the system of equations can be written as, $AX = D$, i.e.,

$$\begin{bmatrix} a_1 & b_1 & c_1 \\ a_2 & b_2 & c_2 \\ a_n & b_n & c_n \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} d_1 \\ d_2 \\ d_n \end{bmatrix}$$

Case I If A is a nonsingular matrix, then its inverse exists. Now

$$AX = D$$

or $A^{-1}(AX) = A^{-1}D$ (premultiplying by A^{-1})

or $(A^{-1}A)X = A^{-1}D$ (by associative property)

or $I X = A^{-1}D$

or $X = A^{-1}D$

This matrix equation provides unique solution for the given system of equations as inverse of a matrix is unique. This method of solving system of equations is known as Matrix Method.

Case II If A is a singular matrix, then $|A| = 0$.

In this case, we calculate $(adj A)$.

If $(adj A) \neq 0$, (0 being zero matrix), then solution does not exist and the system of equations is called inconsistent.

If $(adj A) = 0$, then system may be either consistent or inconsistent according as the system have either infinitely many solutions or no solution.

Example 27 Solve the system of equations

$$\begin{aligned} 2x + y &= 1 \\ x + 2y &= 0 \end{aligned}$$

Solution The system of equations can be written in the form $Ax = b$, where

$$A = \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix}, \quad x = \begin{bmatrix} x \\ y \end{bmatrix} \quad \text{and} \quad b = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

Now, $|A| = -11 \neq 0$, hence, A is nonsingular matrix and so has a unique solution.

Note that
$$A^{-1} = -\frac{1}{11} \begin{bmatrix} 2 & -1 \\ -1 & 2 \end{bmatrix}$$

Therefore
$$x = A^{-1}b = -\frac{1}{11} \begin{bmatrix} 2 & -1 \\ -1 & 2 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

i.e.
$$\begin{bmatrix} x \\ y \end{bmatrix} = -\frac{1}{11} \begin{bmatrix} -1 \\ 11 \end{bmatrix} = \begin{bmatrix} \frac{1}{11} \\ -1 \end{bmatrix}$$

hence
$$x = \frac{1}{11}, y = -1$$

Example 28 Solve the following system of equations by matrix method.

$$\begin{aligned} x - 2y + z &= 0 \\ 2x + y - z &= 1 \\ x - y + 2z &= 0 \end{aligned}$$

Solution The system of equations can be written in the form $Ax = b$, where

$$A = \begin{bmatrix} 1 & -2 & 1 \\ 2 & 1 & -1 \\ 1 & -1 & 2 \end{bmatrix}, \quad x = \begin{bmatrix} x \\ y \\ z \end{bmatrix} \quad \text{and} \quad b = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}$$

We see that

$$|A| = 1(2 - 1) + 2(2 - 1) + 1(-2 - 1) = -1 \neq 0$$

Hence, A is nonsingular and so its inverse exists. Now

$$\begin{aligned} A_{11} &= -1, & A_{12} &= -2, & A_{13} &= -10 \\ A_{21} &= -2, & A_{22} &= -2, & A_{23} &= 1 \\ A_{31} &= -1, & A_{32} &= 2, & A_{33} &= 2 \end{aligned}$$

Therefore
$$A^{-1} = -\frac{1}{10} \begin{bmatrix} -1 & -2 & -1 \\ -2 & -2 & 1 \\ -10 & 1 & 2 \end{bmatrix}$$

So
$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = A^{-1} \begin{bmatrix} 1 \\ 11 \\ 0 \end{bmatrix} = -\frac{1}{10} \begin{bmatrix} -1 & -2 & -1 \\ -2 & -2 & 1 \\ -10 & 1 & 2 \end{bmatrix} \begin{bmatrix} 1 \\ 11 \\ 0 \end{bmatrix}$$

i.e.
$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = -\frac{1}{10} \begin{bmatrix} -1 \\ -2 \\ -10 \end{bmatrix} = \begin{bmatrix} 1 \\ 2 \\ 1 \end{bmatrix}$$

Hence $x = 1, y = 2$ and $z = 1$

Example 29 The sum of three numbers is 10. If we multiply third number by 2 and add second number to it, we get 11. By adding first and third numbers, we get double of the second number. Represent it algebraically and find the numbers using matrix method.

Solution Let first, second and third numbers be denoted by x, y and z , respectively. Then, according to given conditions, we have

$$\begin{aligned} x + y + z &= 10 \\ y + 2z &= 11 \\ x + z &= 2y \text{ or } x - 2y + z = 0 \end{aligned}$$

This system can be written as $A \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} 10 \\ 11 \\ 0 \end{bmatrix}$, where

$$A = \begin{bmatrix} 1 & 1 & 1 \\ 0 & 1 & 2 \\ 1 & -2 & 1 \end{bmatrix}, \begin{bmatrix} x \\ y \\ z \end{bmatrix} \text{ and } \begin{bmatrix} 10 \\ 11 \\ 0 \end{bmatrix}$$

Here $|A| = 1(1+2) - (0-2) + (0-1) = 3 \neq 0$. Now we find $adj A$

$$\begin{aligned} A_{11} &= 1(1+2) = 3, & A_{12} &= -(0-2) = 2, & A_{13} &= -1 \\ A_{21} &= -(1+2) = -3, & A_{22} &= 0, & A_{23} &= -(-2-1) = 3 \\ A_{31} &= (2-1) = 1, & A_{32} &= -(2-0) = -2, & A_{33} &= (1-0) = 1 \end{aligned}$$

∴ Hence
$$\text{adj } A = \begin{bmatrix} a & -b & 2 \\ a & 0 & -c \\ -1 & a & 1 \end{bmatrix}$$

Thus
$$A^{-1} = \frac{1}{|A|} \text{adj } (A) = \frac{1}{a} \begin{bmatrix} a & -b & 2 \\ a & 0 & -c \\ -1 & a & 1 \end{bmatrix}$$

Since
$$X = A^{-1} Y$$

$$X = \frac{1}{a} \begin{bmatrix} a & -b & 2 \\ a & 0 & -c \\ -1 & a & 1 \end{bmatrix} \begin{bmatrix} a \\ 11 \\ 0 \end{bmatrix}$$

or
$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \frac{1}{a} \begin{bmatrix} a^2 - ab + 0 \\ 1a + 0 + 0 \\ -a + a + 0 \end{bmatrix} = \frac{1}{a} \begin{bmatrix} a \\ 1 \\ 2 \end{bmatrix} = \begin{bmatrix} 1 \\ 2 \\ a \end{bmatrix}$$

Thus $x = 1, y = 2, z = a$

EXERCISE 4.6

Examine the consistency of the system of equations in Exercises 1 to 6

- | | | |
|---|--|---|
| 1. $x + 2y = 2$
$2x + 3y = a$ | 2. $2x - y = a$
$x + y = a$ | 3. $x + 3y = a$
$2x + 4y = a$ |
| 4. $x + y + z = 1$
$2x + 3y + 2z = 2$
$ax + ay + 2az = a$ | 5. $3x - y - 2z = 2$
$2y - z = -1$
$3x - 4y = a$ | 6. $3x - y + 4z = a$
$2x + 3y + 4z = 2$
$3x - 2y + 4z = -1$ |

Solve system of linear equations, using matrix method, in Exercises 7 to 14

- | | | |
|--|---|---|
| 7. $3x + 2y = a$
$3x + 4y = a$ | 8. $2x - y = -2$
$3x + 4y = a$ | 9. $3x - 4y = a$
$3x - 5y = a$ |
| 10. $3x + 2y = a$
$3x + 2y = a$ | 11. $2x + y + z = 1$
$x - 2y - z = \frac{a}{2}$
$3y - 4z = a$ | 12. $x - y + z = a$
$2x + y - 4z = 0$
$x + y + z = 2$ |
| 13. $2x + 3y + 4z = a$
$x - 2y + z = -a$
$3x - y - 2z = a$ | 14. $x - y + 2z = a$
$3x + 4y - 4z = -a$
$2x - y + 4z = 12$ | |

15. If $A = \begin{bmatrix} 2 & -1 & 1 \\ 1 & 2 & -1 \\ 1 & 1 & -2 \end{bmatrix}$, find A^{-1} . Using A^{-1} solve the system of equations

$$2x - y + z = 11$$

$$x + 2y - z = -1$$

$$x + y - 2z = -1$$

16. The cost of 1 kg onion, 1 kg wheat and 2 kg rice is Rs 10. The cost of 2 kg onion, 1 kg wheat and 1 kg rice is Rs 10. The cost of 1 kg onion 2 kg wheat and 1 kg rice is Rs 10. Find cost of each item per kg by matrix method.

Miscellaneous Examples

Example 30 If a, b, c are positive and unequal, show that value of the determinant

$$\Delta = \begin{vmatrix} a & b & c \\ b & c & a \\ c & a & b \end{vmatrix} \text{ is negative.}$$

Solution Applying $R_1 \rightarrow R_1 + R_2 + R_3$ to the given determinant, we get

$$\begin{aligned} \Delta &= \begin{vmatrix} a+b+c & b & c \\ a+b+c & c & a \\ a+b+c & a & b \end{vmatrix} = (a+b+c) \begin{vmatrix} 1 & b & c \\ 1 & c & a \\ 1 & a & b \end{vmatrix} \\ &= (a+b+c) \begin{vmatrix} 1 & b & c \\ 0 & c-b & a-c \\ 0 & a-b & b-c \end{vmatrix} \text{ (Applying } R_2 \rightarrow R_2 - R_1, \text{ and } R_3 \rightarrow R_3 - R_1) \\ &= (a+b+c) [(c-b)(b-c) - (a-c)(a-b)] \text{ (Expanding along } R_1) \\ &= (a+b+c)(-a^2 - b^2 - c^2 + ab + bc + ca) \\ &= \frac{-1}{2} (a+b+c)(2a^2 + 2b^2 + 2c^2 - 2ab - 2bc - 2ca) \\ &= \frac{-1}{2} (a+b+c)[(a-b)^2 + (b-c)^2 + (c-a)^2] \end{aligned}$$

which is negative (since $a+b+c > 0$ and $(a-b)^2 + (b-c)^2 + (c-a)^2 > 0$)

Example 31 If a, b, c , are in A.P. find value of

$$\begin{vmatrix} 2y + a & y + a & y + a \\ y + a & y + a & y + b \\ y + a & y + a & 10y + c \end{vmatrix}$$

Solution Applying $R_1 \rightarrow R_1 + R_2 - 2R_3$ to the given determinant, we obtain

$$\begin{vmatrix} 0 & 0 & 0 \\ y + a & y + a & y + b \\ y + a & y + a & 10y + c \end{vmatrix} = 0 \quad (\text{Since } 2b = a + c)$$

Example 32 Show that

$$\Delta = \begin{vmatrix} (y+z)^2 & xy & zx \\ xy & (x+z)^2 & yz \\ xz & yz & (x+y)^2 \end{vmatrix} = 2xyz(x+y+z)$$

Solution Applying $R_1 \rightarrow xR_1, R_2 \rightarrow yR_2, R_3 \rightarrow zR_3$ to Δ and dividing by xyz , we get

$$\Delta = \frac{1}{xyz} \begin{vmatrix} x(y+z)^2 & x^2y & x^2z \\ xy^2 & y(x+z)^2 & y^2z \\ xz^2 & yz^2 & z(x+y)^2 \end{vmatrix}$$

Taking common factors x, y, z from C_1, C_2 and C_3 , respectively, we get

$$\Delta = \frac{xyz}{xyz} \begin{vmatrix} (y+z)^2 & x^2 & x^2 \\ y^2 & (x+z)^2 & y^2 \\ z^2 & z^2 & (x+y)^2 \end{vmatrix}$$

Applying $C_2 \rightarrow C_2 - C_1, C_3 \rightarrow C_3 - C_1$, we have

$$\Delta = \begin{vmatrix} (y+z)^2 & x^2 - (y+z)^2 & x^2 - (y+z)^2 \\ y^2 & (x+z)^2 - y^2 & 0 \\ z^2 & 0 & (x+y)^2 - z^2 \end{vmatrix}$$

Taking common factor $(x + y + z)$ from C_2 and C_3 , we have

$$\Delta = (x + y + z)^2 \begin{vmatrix} (y + z)^2 & x - (y + z) & x - (y + z) \\ y^2 & (x + z) - y & 0 \\ z^2 & 0 & (x + y) - z \end{vmatrix}$$

Applying $R_1 \rightarrow R_1 - (R_2 + R_3)$, we have

$$\Delta = (x + y + z)^2 \begin{vmatrix} 2yz & -2z & -2y \\ y^2 & x - y + z & 0 \\ z^2 & 0 & x + y - z \end{vmatrix}$$

Applying $C_2 \rightarrow (C_2 + \frac{1}{y} C_1)$ and $C_3 \rightarrow (C_3 + \frac{1}{z} C_1)$, we get

$$\Delta = (x + y + z)^2 \begin{vmatrix} 2yz & 0 & 0 \\ y^2 & x + z & \frac{y^2}{z} \\ z^2 & \frac{z^2}{y} & x + y \end{vmatrix}$$

Finally expanding along R_1 , we have

$$\begin{aligned} \Delta &= (x + y + z)^2 (2yz) [(x + z)(x + y) - yz] = (x + y + z)^2 (2yz) (x^2 + xy + xz) \\ &= (x + y + z)^3 (2xyz) \end{aligned}$$

Example 33 Use product $\begin{bmatrix} 1 & -1 & 2 \\ 0 & 2 & -1 \\ 1 & -2 & 1 \end{bmatrix} \begin{bmatrix} -2 & 0 & 1 \\ 1 & 2 & -1 \\ 1 & 1 & -2 \end{bmatrix}$ to solve the system of equations

$$\begin{aligned} x - y + 2z &= 1 \\ 2y - z &= 1 \\ x - 2y + z &= 2 \end{aligned}$$

Solution Consider the product $\begin{bmatrix} 1 & -1 & 2 \\ 0 & 2 & -1 \\ 1 & -2 & 1 \end{bmatrix} \begin{bmatrix} -2 & 0 & 1 \\ 1 & 2 & -1 \\ 1 & 1 & -2 \end{bmatrix}$

$$= \begin{bmatrix} -2 - \square + 12 & 0 - 2 + 2 & 1 + \square - \square \\ 0 + 1 - 1 & 0 + \square - \square & 0 - \square + \square \\ -\square - 1 + 2 & 0 - \square + \square & \square + \square - \square \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\square \text{ence} \quad \begin{bmatrix} 1 & -1 & 2 \\ 0 & 2 & -\square \\ \square & -2 & \square \end{bmatrix}^{-1} = \begin{bmatrix} -2 & 0 & 1 \\ \square & 2 & -\square \\ \square & 1 & -2 \end{bmatrix}$$

Now, given system of equations can be written, in matrix form, as follows

$$\begin{bmatrix} 1 & -1 & 2 \\ 0 & 2 & -\square \\ \square & -2 & \square \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 2 \end{bmatrix}$$

$$\text{or} \quad \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} 1 & -1 & 2 \\ 0 & 2 & -\square \\ \square & -2 & \square \end{bmatrix}^{-1} \begin{bmatrix} 1 \\ 1 \\ 2 \end{bmatrix} = \begin{bmatrix} -2 & 0 & 1 \\ \square & 2 & -\square \\ \square & 1 & -2 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \\ 2 \end{bmatrix}$$

$$= \begin{bmatrix} -2 + 0 + 2 \\ \square + 2 - \square \\ \square + 1 - \square \end{bmatrix} = \begin{bmatrix} 0 \\ \square \\ \square \end{bmatrix}$$

\square \text{ence}

$$x = 0, y = \square \text{ and } z = \square$$

Example 34 Prove that

$$\Delta = \begin{vmatrix} a+bx & c+dx & p+qx \\ ax+b & cx+d & px+q \\ u & v & w \end{vmatrix} = (1-x^2) \begin{vmatrix} a & c & p \\ b & d & q \\ u & v & w \end{vmatrix}$$

Solution Applying $R_1 \rightarrow R_1 - x R_2$ to Δ , we get

$$\begin{aligned} \Delta &= \begin{vmatrix} a(1-x^2) & c(1-x^2) & p(1-x^2) \\ ax+b & cx+d & px+q \\ u & v & w \end{vmatrix} \\ &= (1-x^2) \begin{vmatrix} a & c & p \\ ax+b & cx+d & px+q \\ u & v & w \end{vmatrix} \end{aligned}$$

Applying $R_2 \rightarrow R_2 - x R_1$, we get

$$\Delta = (1-x^2) \begin{vmatrix} a & c & p \\ b & d & q \\ u & v & w \end{vmatrix}$$

Miscellaneous Exercises on Chapter 4

1. Prove that the determinant $\begin{vmatrix} x & \sin \theta & \cos \theta \\ -\sin \theta & -x & 1 \\ \cos \theta & 1 & x \end{vmatrix}$ is independent of θ .

2. Without expanding the determinant, prove that $\begin{vmatrix} a & a^2 & bc \\ b & b^2 & ca \\ c & c^2 & ab \end{vmatrix} = \begin{vmatrix} 1 & a^2 & a^3 \\ 1 & b^2 & b^3 \\ 1 & c^2 & c^3 \end{vmatrix}$.

3. Evaluate $\begin{vmatrix} \cos \alpha \cos \beta & \cos \alpha \sin \beta & -\sin \alpha \\ -\sin \beta & \cos \beta & 0 \\ \sin \alpha \cos \beta & \sin \alpha \sin \beta & \cos \alpha \end{vmatrix}$.

4. If a , b and c are real numbers, and

$$\Delta = \begin{vmatrix} b+c & c+a & a+b \\ c+a & a+b & b+c \\ a+b & b+c & c+a \end{vmatrix} = 0,$$

Show that either $a + b + c = 0$ or $a = b = c$.

5. Solve the equation $\begin{vmatrix} x+a & x & x \\ x & x+a & x \\ x & x & x+a \end{vmatrix} = 0, a \neq 0$

6. Prove that $\begin{vmatrix} a^2 & bc & ac+c^2 \\ a^2+ab & b^2 & ac \\ ab & b^2+bc & c^2 \end{vmatrix} = a^2b^2c^2$

7. If $A^{-1} = \begin{bmatrix} \square & -1 & 1 \\ -1\square & \square & -\square \\ \square & -2 & 2 \end{bmatrix}$ and $\square = \begin{bmatrix} 1 & 2 & -2 \\ -1 & \square & 0 \\ 0 & -2 & 1 \end{bmatrix}$, find $(A\square)^{-1}$

8. Let $A = \begin{bmatrix} 1 & -2 & 1 \\ -2 & \square & 1 \\ 1 & 1 & \square \end{bmatrix}$. Verify that

(i) $[\text{adj } A]^{-1} = \text{adj } (A^{-1})$ (ii) $(A^{-1})^{-1} = A$

9. Evaluate $\begin{vmatrix} x & y & x+y \\ y & x+y & x \\ x+y & x & y \end{vmatrix}$

10. Evaluate $\begin{vmatrix} 1 & x & y \\ 1 & x+y & y \\ 1 & x & x+y \end{vmatrix}$

Using properties of determinants in Exercises 11 to 13, prove that

11. $\begin{vmatrix} \alpha & \alpha^2 & \beta+\gamma \\ \beta & \beta^2 & \gamma+\alpha \\ \gamma & \gamma^2 & \alpha+\beta \end{vmatrix} = (\beta-\gamma)(\gamma-\alpha)(\alpha-\beta)(\alpha+\beta+\gamma)$

12. $\begin{vmatrix} x & x^2 & 1+px \\ y & y^2 & 1+py \\ z & z^2 & 1+pz \end{vmatrix} = (1+pxyz)(x-y)(y-z)(z-x)$, where p is any scalar.

13. $\begin{vmatrix} \square a & -a+b & -a+c \\ -b+a & \square b & -b+c \\ -c+a & -c+b & \square c \end{vmatrix} = \square(a+b+c)(ab+bc+ca)$

14. $\begin{vmatrix} 1 & 1+p & 1+p+q \\ 2 & \square+2p & \square+\square p+2q \\ \square & \square+\square p & 10+\square p+\square q \end{vmatrix} = 1$ 15. $\begin{vmatrix} \sin \alpha & \cos \alpha & \cos(\alpha+\delta) \\ \sin \beta & \cos \beta & \cos(\beta+\delta) \\ \sin \gamma & \cos \gamma & \cos(\gamma+\delta) \end{vmatrix} = 0$

16. Solve the system of equations

$$\frac{2}{x} + \frac{\square}{y} + \frac{10}{z} = \square$$

$$\frac{1}{x} - \frac{1}{y} + \frac{1}{z} = 1$$

$$\frac{1}{x} + \frac{1}{y} - \frac{20}{z} = 2$$

Choose the correct answer in Exercise 10 to 100

17. If a, b, c , are in A.P. then the determinant

$$\begin{vmatrix} x+2 & x+a & x+2a \\ x+a & x+b & x+2b \\ x+a & x+b & x+2c \end{vmatrix} \text{ is}$$

- (A) 0 (B) 1 (C) x (D) $2x$

18. If x, y, z are non-zero real numbers, then the inverse of matrix $A = \begin{bmatrix} x & 0 & 0 \\ 0 & y & 0 \\ 0 & 0 & z \end{bmatrix}$ is

(A) $\begin{bmatrix} x^{-1} & 0 & 0 \\ 0 & y^{-1} & 0 \\ 0 & 0 & z^{-1} \end{bmatrix}$

(B) $xyz \begin{bmatrix} x^{-1} & 0 & 0 \\ 0 & y^{-1} & 0 \\ 0 & 0 & z^{-1} \end{bmatrix}$

(C) $\frac{1}{xyz} \begin{bmatrix} x & 0 & 0 \\ 0 & y & 0 \\ 0 & 0 & z \end{bmatrix}$

(D) $\frac{1}{xyz} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$

19. Let $A = \begin{bmatrix} 1 & \sin \theta & 1 \\ -\sin \theta & 1 & \sin \theta \\ -1 & -\sin \theta & 1 \end{bmatrix}$, where $0 \leq \theta \leq 2\pi$. Then

- (A) $\text{Det}(A) = 0$ (B) $\text{Det}(A) \in (2, \infty)$
 (C) $\text{Det}(A) \in (2, \infty)$ (D) $\text{Det}(A) \in [2, \infty)$

Summary

- ◆ Determinant of a matrix $A = [a_{ij}]_{1 \times 1}$ is given by $|A| = a_{11}$

- ◆ Determinant of a matrix $A = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}$ is given by

$$|A| = \begin{vmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{vmatrix} = a_{11} a_{22} - a_{12} a_{21}$$

- ◆ Determinant of a matrix $A = \begin{bmatrix} a_1 & b_1 & c_1 \\ a_2 & b_2 & c_2 \\ a_{\square} & b_{\square} & c_{\square} \end{bmatrix}$ is given by (expanding along R_1)

$$|A| = \begin{vmatrix} a_1 & b_1 & c_1 \\ a_2 & b_2 & c_2 \\ a_{\square} & b_{\square} & c_{\square} \end{vmatrix} = a_1 \begin{vmatrix} b_2 & c_2 \\ b_{\square} & c_{\square} \end{vmatrix} - b_1 \begin{vmatrix} a_2 & c_2 \\ a_{\square} & c_{\square} \end{vmatrix} + c_1 \begin{vmatrix} a_2 & b_2 \\ a_{\square} & b_{\square} \end{vmatrix}$$

For any square matrix A, the |A| satisfy following properties.

- ◆ $|A'| = |A|$ where $A' =$ transpose of A .
- ◆ If we interchange any two rows (or columns), then sign of determinant changes.
- ◆ If any two rows or any two columns are identical or proportional, then value of determinant is zero.
- ◆ If we multiply each element of a row or a column of a determinant by constant k , then value of determinant is multiplied by k .
- ◆ Multiplying a determinant by k means multiply elements of only one row (or one column) by k .
- ◆ If $A = [a_{ij}]_{n \times n}$, then $|k \cdot A| = k^n |A|$
- ◆ If elements of a row or a column in a determinant can be expressed as sum of two or more elements, then the given determinant can be expressed as sum of two or more determinants.
- ◆ If to each element of a row or a column of a determinant the equimultiples of corresponding elements of other rows or columns are added, then value of determinant remains same.

- ◆ Area of a triangle with vertices (x_1, y_1) , (x_2, y_2) and (x_3, y_3) is given by

$$\Delta = \frac{1}{2} \begin{vmatrix} x_1 & y_1 & 1 \\ x_2 & y_2 & 1 \\ x_3 & y_3 & 1 \end{vmatrix}$$

- ◆ Minor of an element a_{ij} of the determinant of matrix A is the determinant obtained by deleting i^{th} row and j^{th} column and denoted by M_{ij} .

- ◆ Cofactor of a_{ij} of given by $A_{ij} = (-1)^{i+j} M_{ij}$

- ◆ Value of determinant of a matrix A is obtained by sum of product of elements of a row (or a column) with corresponding cofactors. For example,

$$|A| = a_{11} A_{11} + a_{12} A_{12} + a_{13} A_{13}$$

- ◆ If elements of one row (or column) are multiplied with cofactors of elements of any other row (or column), then their sum is zero. For example, $a_{11} A_{21} + a_{12} A_{22} + a_{13} A_{23} = 0$

- ◆ If $A = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}$, then $\text{adj } A = \begin{bmatrix} A_{11} & A_{21} & A_{31} \\ A_{12} & A_{22} & A_{32} \\ A_{13} & A_{23} & A_{33} \end{bmatrix}$, where A_{ij} is cofactor of a_{ij}

- ◆ $A (\text{adj } A) = (\text{adj } A) A = |A| I$, where A is square matrix of order n .

- ◆ A square matrix A is said to be singular or non-singular according as $|A| = 0$ or $|A| \neq 0$.

- ◆ If $A \square = \square A = I$, where \square is square matrix, then \square is called inverse of A. Also $A^{-1} = \square$ or $\square^{-1} = A$ and hence $(A^{-1})^{-1} = A$.

- ◆ A square matrix A has inverse if and only if A is non-singular.

- ◆ $A^{-1} = \frac{1}{|A|} (\text{adj } A)$

- ◆ If $a_1 x + b_1 y + c_1 z = d_1$
 $a_2 x + b_2 y + c_2 z = d_2$
 $a_3 x + b_3 y + c_3 z = d_3$

then these equations can be written as $A \square = \square$, where

$$A = \begin{bmatrix} a_1 & b_1 & c_1 \\ a_2 & b_2 & c_2 \\ a_3 & b_3 & c_3 \end{bmatrix}, \square = \begin{bmatrix} x \\ y \\ z \end{bmatrix} \text{ and } \square = \begin{bmatrix} d_1 \\ d_2 \\ d_3 \end{bmatrix}$$

- ◆ Unique solution of equation $Ax = b$ is given by $x = A^{-1}b$, where $|A| \neq 0$.
- ◆ A system of equation is consistent or inconsistent according as its solution exists or not.
- ◆ For a square matrix A in matrix equation $Ax = b$
 - (i) $|A| \neq 0$, there exists unique solution
 - (ii) $|A| \neq 0$ and $(adj A)b \neq 0$, then there exists no solution
 - (iii) $|A| \neq 0$ and $(adj A)b = 0$, then system may or may not be consistent.

Historical Note

The Chinese method of representing the coefficients of the unknowns of several linear equations by using rods on a calculating board naturally led to the discovery of simple method of elimination. The arrangement of rods was precisely that of the numbers in a determinant. The Chinese, therefore, early developed the idea of subtracting columns and rows as in simplification of a determinant [Mikami, *China*, pp 10, 11]

Seki Kowa, the greatest of the Japanese Mathematicians of seventeenth century in his work [*Kai Fukudai no Ho*] in 1658 showed that he had the idea of determinants and of their expansion. But he used this device only in eliminating a quantity from two equations and not directly in the solution of a set of simultaneous linear equations. T. Hayashi, [*The Fukudo and Determinants in Japanese Mathematics*], in the proc. of the Tokyo Math. Soc., 1911

Condoronde was the first to recognise determinants as independent functions. He may be called the formal founder. Laplace (1749), gave general method of expanding a determinant in terms of its complementary minors. In 1751 Lagrange treated determinants of the second and third orders and used them for purpose other than the solution of equations. In 1801, Gauss used determinants in his theory of numbers.

The next great contributor was Jacques Philippe Marie Binet, (1782) who stated the theorem relating to the product of two matrices of m columns and n rows, which for the special case of $m = n$ reduces to the multiplication theorem.

Also on the same day, Cauchy (1812) presented one on the same subject. He used the word 'determinant' in its present sense. He gave the proof of multiplication theorem more satisfactory than Binet's.

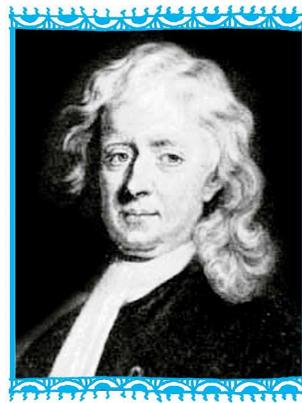
The greatest contributor to the theory was Carl Gustav Jacob Jacobi, after this the word determinant received its final acceptance.

CONTINUITY AND DIFFERENTIABILITY

❖ *The whole of science is nothing more than a refinement of everyday thinking.* — ALBERT EINSTEIN ❖

5.1 Introduction

This chapter is essentially a continuation of our study of differentiation of functions in Class XI. We had learnt to differentiate certain functions like polynomial functions and trigonometric functions. In this chapter, we introduce the very important concepts of continuity, differentiability and relations between them. We will also learn differentiation of inverse trigonometric functions. Further, we introduce a new class of functions called exponential and logarithmic functions. These functions lead to powerful techniques of differentiation. We illustrate certain geometrically obvious conditions through differential calculus. In the process, we will learn some fundamental theorems in this area.



Sir Issac Newton
(1642-1727)

5.2 Continuity

We start the section with two informal examples to get a feel of continuity. Consider the function

$$f(x) = \begin{cases} 1, & \text{if } x \leq 0 \\ 2, & \text{if } x > 0 \end{cases}$$

This function is of course defined at every point of the real line. Graph of this function is given in the Fig 5.1. One can deduce from the graph that the value of the function at *nearby* points on *x*-axis remain *close* to each other except at $x = 0$. At the points near and to the left of 0, i.e., at points like $-0.1, -0.01, -0.001$, the value of the function is 1. At the points near and to the right of 0, i.e., at points like $0.1, 0.01,$

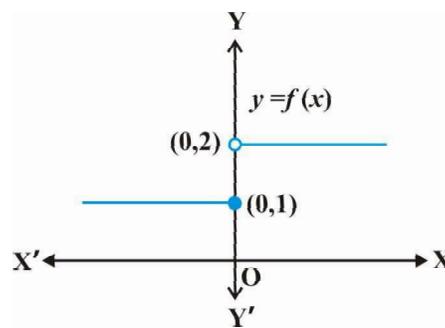


Fig 5.1

0.001, the value of the function is 2. Using the language of left and right hand limits, we may say that the left (respectively right) hand limit of f at 0 is 1 (respectively 2). In particular the left and right hand limits do not coincide. We also observe that the value of the function at $x = 0$ coincides with the left hand limit. Note that when we try to draw the graph, we cannot draw it in one stroke, i.e., without lifting pen from the plane of the paper, we cannot draw the graph of this function. In fact, we need to lift the pen when we come to 0 from left. This is one instance of function being not continuous at $x = 0$.

Now, consider the function defined as

$$f(x) = \begin{cases} 1, & \text{if } x \neq 0 \\ 2, & \text{if } x = 0 \end{cases}$$

This function is also defined at every point. Left and the right hand limits at $x = 0$ are both equal to 1. But the value of the function at $x = 0$ equals 2 which does not coincide with the common value of the left and right hand limits. Again, we note that we cannot draw the graph of the function without lifting the pen. This is yet another instance of a function being not continuous at $x = 0$.

Alternatively, we may say that a function is continuous at a fixed point if we can draw the graph of the function *around* that point without lifting the pen from the plane of the paper.

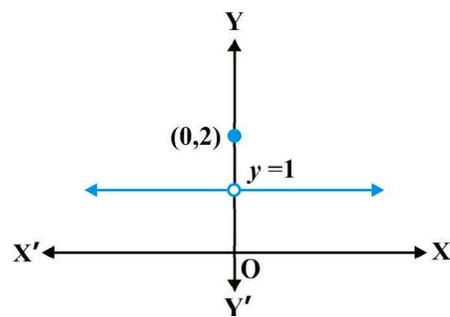


Fig 5.2

Mathematically, it may be phrased precisely as follows

Definition 1 Suppose f is a real function on a subset of the real numbers and let c be a point in the domain of f . Then f is continuous at c if

$$\lim_{x \rightarrow c} f(x) = f(c)$$

More elaborately, if the left hand limit, right hand limit and the value of the function at $x = c$ exist and equal to each other, then f is said to be continuous at $x = c$. Recall that if the right hand and left hand limits at $x = c$ coincide, then we say that the common value is the limit of the function at $x = c$. Hence we may also rephrase the definition of continuity as follows *a function is continuous at $x = c$ if the function is defined at $x = c$ and if the value of the function at $x = c$ equals the limit of the function at $x = c$* . If f is not continuous at c , we say f is *discontinuous* at c and c is called a *point of discontinuity* of f .

Example 1 Check the continuity of the function f given by $f(x) = 2x + 3$ at $x = 1$.

Solution First note that the function is defined at the given point $x = 1$ and its value is 5. Then find the limit of the function at $x = 1$. Clearly

$$\lim_{x \rightarrow 1} f(x) = \lim_{x \rightarrow 1} (2x + 3) = 2(1) + 3 = 5$$

Thus $\lim_{x \rightarrow 1} f(x) = 5 = f(1)$

ence, f is continuous at $x = 1$.

Example 2 Examine whether the function f given by $f(x) = x^2$ is continuous at $x = 0$.

Solution First note that the function is defined at the given point $x = 0$ and its value is 0. Then find the limit of the function at $x = 0$. Clearly

$$\lim_{x \rightarrow 0} f(x) = \lim_{x \rightarrow 0} x^2 = 0^2 = 0$$

Thus $\lim_{x \rightarrow 0} f(x) = 0 = f(0)$

ence, f is continuous at $x = 0$.

Example 3 Discuss the continuity of the function f given by $f(x) = |x|$ at $x = 0$.

Solution by definition

$$f(x) = \begin{cases} -x, & \text{if } x < 0 \\ x, & \text{if } x \geq 0 \end{cases}$$

Clearly the function is defined at 0 and $f(0) = 0$. Left hand limit of f at 0 is

$$\lim_{x \rightarrow 0^-} f(x) = \lim_{x \rightarrow 0^-} (-x) = 0$$

imilarly, the right hand limit of f at 0 is

$$\lim_{x \rightarrow 0^+} f(x) = \lim_{x \rightarrow 0^+} x = 0$$

Thus, the left hand limit, right hand limit and the value of the function coincide at $x = 0$. Hence, f is continuous at $x = 0$.

Example 4 Show that the function f given by

$$f(x) = \begin{cases} x + 1, & \text{if } x \neq 0 \\ 1, & \text{if } x = 0 \end{cases}$$

is not continuous at $x = 0$.

Solution The function is defined at $x = 0$ and its value at $x = 0$ is 1. When $x \neq 0$, the function is given by a polynomial. Hence,

$$\lim_{x \rightarrow 0} f(x) = \lim_{x \rightarrow 0} (x + 1) = 1 + 1 = 2$$

Since the limit of f at $x = 0$ does not coincide with $f(0)$, the function is not continuous at $x = 0$. It may be noted that $x = 0$ is the only point of discontinuity for this function.

Example 5 Check the points where the constant function $f(x) = k$ is continuous.

Solution The function is defined at all real numbers and by definition, its value at any real number equals k . Let c be any real number. Then

$$\lim_{x \rightarrow c} f(x) = \lim_{x \rightarrow c} k = k$$

Since $f(c) = k = \lim_{x \rightarrow c} f(x)$ for any real number c , the function f is continuous at every real number.

Example 6 Prove that the identity function on real numbers given by $f(x) = x$ is continuous at every real number.

Solution The function is clearly defined at every point and $f(c) = c$ for every real number c . Also,

$$\lim_{x \rightarrow c} f(x) = \lim_{x \rightarrow c} x = c$$

Thus, $\lim_{x \rightarrow c} f(x) = c = f(c)$ and hence the function is continuous at every real number.

Having defined continuity of a function at a given point, now we make a natural extension of this definition to discuss continuity of a function.

Definition 2 A real function f is said to be continuous if it is continuous at every point in the domain of f .

This definition requires a bit of elaboration. Suppose f is a function defined on a closed interval $[a, b]$, then for f to be continuous, it needs to be continuous at every point in $[a, b]$ including the end points a and b . Continuity of f at a means

$$\lim_{x \rightarrow a^+} f(x) = f(a)$$

and continuity of f at b means

$$\lim_{x \rightarrow b^-} f(x) = f(b)$$

Observe that $\lim_{x \rightarrow a^-} f(x)$ and $\lim_{x \rightarrow b^+} f(x)$ do not make sense. As a consequence of this definition, if f is defined only at one point, it is continuous there, i.e., if the domain of f is a singleton, f is a continuous function.

Example 7 Is the function defined by $f(x) = |x|$, a continuous function

Solution We may rewrite f as

$$f(x) = \begin{cases} -x, & \text{if } x < 0 \\ x, & \text{if } x \geq 0 \end{cases}$$

By example 6, we know that f is continuous at $x = 0$.

Let c be a real number such that $c < 0$. Then $f(c) = -c$. Also

$$\lim_{x \rightarrow c} f(x) = \lim_{x \rightarrow c} (-x) = -c \quad (\text{Why})$$

Since $\lim_{x \rightarrow c} f(x) = f(c)$, f is continuous at all negative real numbers.

Now, let c be a real number such that $c > 0$. Then $f(c) = c$. Also

$$\lim_{x \rightarrow c} f(x) = \lim_{x \rightarrow c} x = c \quad (\text{Why})$$

Since $\lim_{x \rightarrow c} f(x) = f(c)$, f is continuous at all positive real numbers. Hence, f is continuous at all points.

Example 8 Discuss the continuity of the function f given by $f(x) = x^2 - 1$.

Solution Clearly f is defined at every real number c and its value at c is $c^2 - 1$. We also know that

$$\lim_{x \rightarrow c} f(x) = \lim_{x \rightarrow c} (x^2 - 1) = c^2 - 1$$

Thus $\lim_{x \rightarrow c} f(x) = f(c)$, and hence f is continuous at every real number. This means f is a continuous function.

Example 9 Discuss the continuity of the function f defined by $f(x) = \frac{1}{x}$, $x \neq 0$.

Solution Fix any non zero real number c , we have

$$\lim_{x \rightarrow c} f(x) = \lim_{x \rightarrow c} \frac{1}{x} = \frac{1}{c}$$

Also, since for $c \neq 0$, $f(c) = \frac{1}{c}$, we have $\lim_{x \rightarrow c} f(x) = f(c)$ and hence, f is continuous at every point in the domain of f . Thus f is a continuous function.

We take this opportunity to explain the concept of *infinity*. This we do by analysing the function $f(x) = \frac{1}{x}$ near $x = 0$. To carry out this analysis we follow the usual trick of finding the value of the function at real numbers *close* to 0. Essentially we are trying to find the right hand limit of f at 0. We tabulate this in the following (Table 5.1).

Table 5.1

x	1	0.0.2	0.1 = 10 ⁻¹	0.01 = 10 ⁻²	0.001 = 10 ⁻³	10 ⁻ⁿ
$f(x)$	1 5	10	100 = 10 ²	1000 = 10 ³	10 ⁿ

We observe that as x gets closer to 0 from the right, the value of $f(x)$ shoots up higher. This may be rephrased as the value of $f(x)$ may be made larger than any given number by choosing a positive real number *very close* to 0. In symbols, we write

$$\lim_{x \rightarrow 0^+} f(x) = +\infty$$

(to be read as the right hand limit of $f(x)$ at 0 is plus infinity). We wish to emphasise that $+\infty$ is NOT a real number and hence the right hand limit of f at 0 does not exist (as a real number).

Similarly, the left hand limit of f at 0 may be found. The following table is self explanatory.

Table 5.2

x	-1	-0.1	-0.2 = -10 ⁻¹	-10 ⁻²	-10 ⁻³	-10 ⁻ⁿ
$f(x)$	-1	-....	-5	-10	-100 = -10 ²	-10 ⁿ

From the Table 5.2, we deduce that the value of $f(x)$ may be made smaller than any given number by choosing a negative real number *very close* to 0. In symbols, we write

$$\lim_{x \rightarrow 0^-} f(x) = -\infty$$

(to be read as the left hand limit of $f(x)$ at 0 is minus infinity). Again, we wish to emphasise that $-\infty$ is NOT a real number and hence the left hand limit of f at 0 does not exist (as a real number). The graph of the reciprocal function given in Fig 5. is a geometric representation of the above mentioned facts.

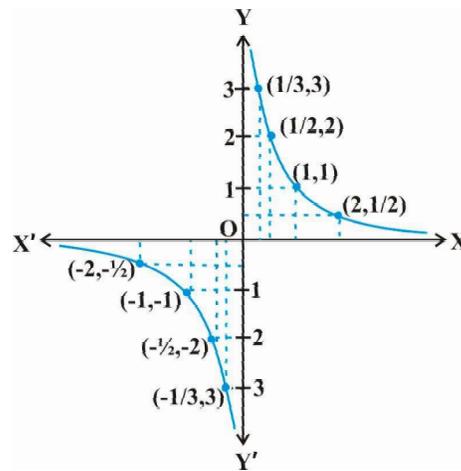


Fig 5.3

Example 10 Discuss the continuity of the function f defined by

$$f(x) = \begin{cases} x + 2, & \text{if } x \leq 1 \\ x - 2, & \text{if } x > 1 \end{cases}$$

Solution The function f is defined at all points of the real line.

Case 1 If $c < 1$, then $f(c) = c + 2$. Therefore, $\lim_{x \rightarrow c} f(x) = \lim_{x \rightarrow c} (x + 2) = c + 2$

Thus, f is continuous at all real numbers less than 1.

Case 2 If $c > 1$, then $f(c) = c - 2$. Therefore,

$$\lim_{x \rightarrow c} f(x) = \lim_{x \rightarrow c} (x - 2) = c - 2 = f(c)$$

Thus, f is continuous at all points $x > 1$.

Case 3 If $c = 1$, then the left hand limit of f at $x = 1$ is

$$\lim_{x \rightarrow 1^-} f(x) = \lim_{x \rightarrow 1^-} (x + 2) = 1 + 2 = 3$$

The right hand limit of f at $x = 1$ is

$$\lim_{x \rightarrow 1^+} f(x) = \lim_{x \rightarrow 1^+} (x - 2) = 1 - 2 = -1$$

Since the left and right hand limits of f at $x = 1$ do not coincide, f is not continuous at $x = 1$. Hence $x = 1$ is the only point of discontinuity of f . The graph of the function is given in Fig 5.4.

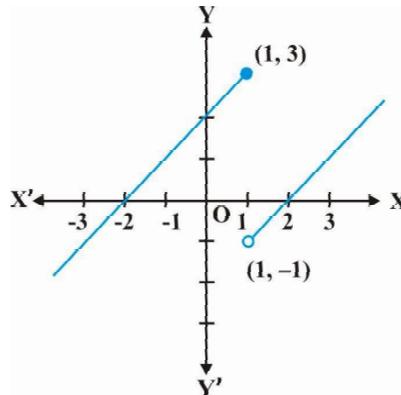


Fig 5.4

Example 11 Find all the points of discontinuity of the function f defined by

$$f(x) = \begin{cases} x + 2, & \text{if } x < 1 \\ 0, & \text{if } x = 1 \\ x - 2, & \text{if } x > 1 \end{cases}$$

Solution As in the previous example we find that f is continuous at all real numbers $x \neq 1$. The left hand limit of f at $x = 1$ is

$$\lim_{x \rightarrow 1^-} f(x) = \lim_{x \rightarrow 1^-} (x + 2) = 1 + 2 = 3$$

The right hand limit of f at $x = 1$ is

$$\lim_{x \rightarrow 1^+} f(x) = \lim_{x \rightarrow 1^+} (x - 2) = 1 - 2 = -1$$

Since, the left and right hand limits of f at $x = 1$ do not coincide, f is not continuous at $x = 1$. Hence $x = 1$ is the only point of discontinuity of f . The graph of the function is given in the Fig 5.5.

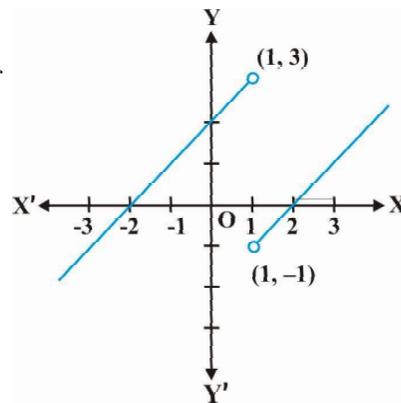


Fig 5.5

Example 12 discuss the continuity of the function defined by

$$f(x) = \begin{cases} x + 2, & \text{if } x < 0 \\ -x + 2, & \text{if } x > 0 \end{cases}$$

Solution Observe that the function is defined at all real numbers except at 0. Domain of definition of this function is

$$D_f = D_1 \cup D_2 \text{ where } D_1 = \{x \in \mathbf{R} \mid x < 0\} \text{ and } D_2 = \{x \in \mathbf{R} \mid x > 0\}$$

Case 1 If $c \in D_1$, then $\lim_{x \rightarrow c} f(x) = \lim_{x \rightarrow c} (x + 2) = c + 2 = f(c)$ and hence f is continuous in D_1 .

Case 2 If $c \in D_2$, then $\lim_{x \rightarrow c} f(x) = \lim_{x \rightarrow c} (-x + 2) = -c + 2 = f(c)$ and hence f is continuous in D_2 .

Since f is continuous at all points in the domain of f , we deduce that f is continuous. Graph of this function is given in the Fig 5.6. Note that to graph this function we need to lift the pen from the plane of the paper, but we need to do that only for those points where the function is not defined.

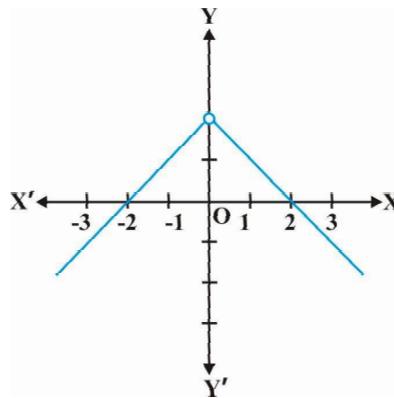


Fig 5.6

Example 13 discuss the continuity of the function f given by

$$f(x) = \begin{cases} x, & \text{if } x \geq 0 \\ x^2, & \text{if } x < 0 \end{cases}$$

Solution Clearly the function is defined at every real number. Graph of the function is given in Fig 5.7. By inspection, it seems prudent to partition the domain of definition of f into three disjoint subsets of the real line.

Let $D_1 = \{x \in \mathbf{R} \mid x < 0\}$, $D_2 = \{0\}$ and $D_3 = \{x \in \mathbf{R} \mid x > 0\}$

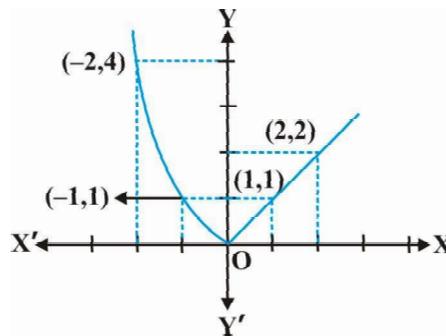


Fig 5.7

Case 1 At any point in D_1 , we have $f(x) = x^2$ and it is easy to see that it is continuous there (see example 2).

Case 2 At any point in D_3 , we have $f(x) = x$ and it is easy to see that it is continuous there (see example 2).

Case 3 Now we analyse the function at $x = 0$. The value of the function at 0 is $f(0) = 0$. The left hand limit of f at 0 is

$$\lim_{x \rightarrow 0^-} f(x) = \lim_{x \rightarrow 0^-} x^2 = 0^2 = 0$$

The right hand limit of f at 0 is

$$\lim_{x \rightarrow 0^+} f(x) = \lim_{x \rightarrow 0^+} x = 0$$

Thus $\lim_{x \rightarrow 0} f(x) = 0 = f(0)$ and hence f is continuous at 0. This means that f is continuous at every point in its domain and hence, f is a continuous function.

Example 14 Show that every polynomial function is continuous.

Solution Recall that a function p is a polynomial function if it is defined by $p(x) = a_0 + a_1x + \dots + a_nx^n$ for some natural number n , $a_n \neq 0$ and $a_i \in \mathbf{R}$. Clearly this function is defined for every real number. For a fixed real number c , we have

$$\lim_{x \rightarrow c} p(x) = p(c)$$

By definition, p is continuous at c . Since c is any real number, p is continuous at every real number and hence p is a continuous function.

Example 15 Find all the points of discontinuity of the greatest integer function defined by $f(x) = [x]$, where $[x]$ denotes the greatest integer less than or equal to x .

Solution First observe that f is defined for all real numbers. Graph of the function is given in Fig 5.8. From the graph it looks like that f is discontinuous at every integral point. Now we explore, if this is true.

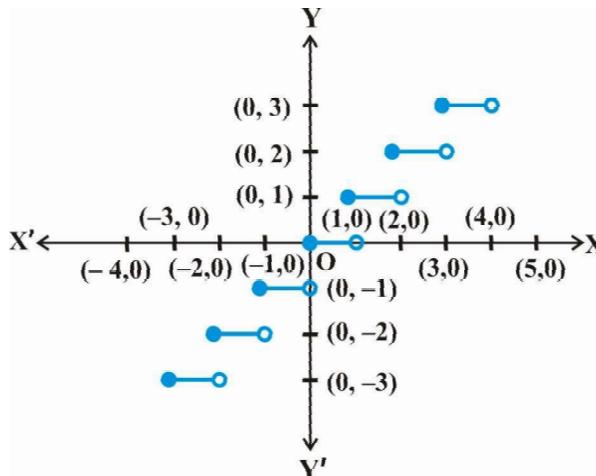


Fig 5.8

Case 1 Let c be a real number which is not equal to any integer. It is evident from the graph that for all real numbers *close* to c the value of the function is equal to c i.e.,

$\lim_{x \rightarrow c} f(x) = \lim_{x \rightarrow c} x = c$. Also $f(c) = c$ and hence the function is continuous at all real numbers not equal to integers.

Case 2 Let c be an integer. Then we can find a sufficiently small real number $r > 0$ such that $c - r = c - 1$ whereas $c + r = c$.

This, in terms of limits mean that

$$\lim_{x \rightarrow c^-} f(x) = c - 1, \quad \lim_{x \rightarrow c^+} f(x) = c$$

Since these limits cannot be equal to each other for any c , the function is discontinuous at every integral point.

5.2.1 Algebra of continuous functions

In the previous class, after having understood the concept of limits, we learnt some algebra of limits. Analogously, now we will study some algebra of continuous functions. Since continuity of a function at a point is entirely dictated by the limit of the function at that point, it is reasonable to expect results analogous to the case of limits.

Theorem 1 Suppose f and g be two real functions continuous at a real number c . Then

- (1) $f + g$ is continuous at $x = c$.
- (2) $f - g$ is continuous at $x = c$.
- (3) $f \cdot g$ is continuous at $x = c$.
- (4) $\left(\frac{f}{g}\right)$ is continuous at $x = c$, (provided $g(c) \neq 0$).

Proof We are investigating continuity of $(f + g)$ at $x = c$. Clearly it is defined at $x = c$. We have

$$\begin{aligned} \lim_{x \rightarrow c} (f + g)(x) &= \lim_{x \rightarrow c} (f(x) + g(x)) && \text{(by definition of } f + g) \\ &= \lim_{x \rightarrow c} f(x) + \lim_{x \rightarrow c} g(x) && \text{(by the theorem on limits)} \\ &= f(c) + g(c) && \text{(as } f \text{ and } g \text{ are continuous)} \\ &= (f + g)(c) && \text{(by definition of } f + g) \end{aligned}$$

Hence, $f + g$ is continuous at $x = c$.

Proofs for the remaining parts are similar and left as an exercise to the reader.

Remarks

- (i) As a special case of (i) above, if f is a constant function, i.e., $f(x) = \lambda$ for some real number λ , then the function $(\lambda \square g)$ defined by $(\lambda \square g)(x) = \lambda \square g(x)$ is also continuous. In particular if $\lambda = -1$, the continuity of f implies continuity of $-f$.
- (ii) As a special case of (i) above, if f is the constant function $f(x) = \lambda$, then the function $\frac{\lambda}{g}$ defined by $\frac{\lambda}{g}(x) = \frac{\lambda}{g(x)}$ is also continuous wherever $g(x) \neq 0$. In particular, the continuity of g implies continuity of $\frac{1}{g}$.

The above theorem can be exploited to generate many continuous functions. They also aid in deciding if certain functions are continuous or not. The following examples illustrate this

Example 16 Prove that every rational function is continuous.

Solution Recall that every rational function f is given by

$$f(x) = \frac{p(x)}{q(x)}, \quad q(x) \neq 0$$

where p and q are polynomial functions. The domain of f is all real numbers except points at which q is zero. Since polynomial functions are continuous (Example 1), f is continuous by (i) of Theorem 1.

Example 17 Discuss the continuity of sine function.

Solution To see this we use the following facts

$$\lim_{x \rightarrow 0} \sin x = 0$$

We have not proved it, but it is intuitively clear from the graph of $\sin x$ near 0.

Now, observe that $f(x) = \sin x$ is defined for every real number. Let c be a real number. Let $x = c + h$. If $x \rightarrow c$ we know that $h \rightarrow 0$. Therefore

$$\begin{aligned} \lim_{x \rightarrow c} f(x) &= \lim_{x \rightarrow c} \sin x \\ &= \lim_{h \rightarrow 0} \sin(c + h) \\ &= \lim_{h \rightarrow 0} \sin c \cos h + \cos c \sin h \\ &= \lim_{h \rightarrow 0} \sin c \cos h + \lim_{h \rightarrow 0} \cos c \sin h \\ &= \sin c \cdot 1 + \cos c \cdot 0 = \sin c = f(c) \end{aligned}$$

Thus $\lim_{x \rightarrow c} f(x) = f(c)$ and hence f is a continuous function.

Remark A similar proof may be given for the continuity of cosine function.

Example 18 Prove that the function defined by $f(x) = \tan x$ is a continuous function.

Solution The function $f(x) = \tan x = \frac{\sin x}{\cos x}$. This is defined for all real numbers such

that $\cos x \neq 0$, i.e., $x \neq (2n+1)\frac{\pi}{2}$. We have just proved that both sine and cosine functions are continuous. Thus $\tan x$ being a quotient of two continuous functions is continuous wherever it is defined.

An interesting fact is the behaviour of continuous functions with respect to composition of functions. Recall that if f and g are two real functions, then

$$(f \circ g)(x) = f(g(x))$$

is defined whenever the range of g is a subset of domain of f . The following theorem (stated without proof) captures the continuity of composite functions.

Theorem 2 Suppose f and g are real valued functions such that $(f \circ g)$ is defined at c . If g is continuous at c and if f is continuous at $g(c)$, then $(f \circ g)$ is continuous at c .

The following examples illustrate this theorem.

Example 19 Prove that the function defined by $f(x) = \sin(x^2)$ is a continuous function.

Solution Observe that the function is defined for every real number. The function f may be thought of as a composition $g \circ h$ of the two functions g and h , where $g(x) = \sin x$ and $h(x) = x^2$. Since both g and h are continuous functions, by Theorem 2, it can be deduced that f is a continuous function.

Example 20 Prove that the function f defined by

$$f(x) = 1 - x|x|,$$

where x is any real number, is a continuous function.

Solution Define g by $g(x) = 1 - x|x|$ and h by $h(x) = x$ for all real x . Then

$$\begin{aligned} (h \circ g)(x) &= h(g(x)) \\ &= h(1 - x|x|) \\ &= 1 - x|x| = f(x) \end{aligned}$$

In Example 20, we have seen that h is a continuous function. Since g being a sum of a polynomial function and the modulus function is continuous, it then follows that f being a composite of two continuous functions is continuous.

EXERCISE 5.1

1. Prove that the function $f(x) = 5x - 1$ is continuous at $x = 0$, at $x = -1$ and at $x = 5$.
2. Examine the continuity of the function $f(x) = 2x^2 - 1$ at $x = 1$.
3. Examine the following functions for continuity.

(a) $f(x) = x - 5$ (b) $f(x) = \frac{1}{x-5}, x \neq 5$

(c) $f(x) = \frac{x^2 - 25}{x + 5}, x \neq -5$ (d) $f(x) = x - 5$

4. Prove that the function $f(x) = x^n$ is continuous at $x = n$, where n is a positive integer.
5. Is the function f defined by

$$f(x) = \begin{cases} x, & \text{if } x \leq 1 \\ 5, & \text{if } x > 1 \end{cases}$$

continuous at $x = 0$ At $x = 1$ At $x = 2$

Find all points of discontinuity of f , where f is defined by

6. $f(x) = \begin{cases} 2x + 1, & \text{if } x \leq 2 \\ 2x - 1, & \text{if } x > 2 \end{cases}$ 7. $f(x) = \begin{cases} x + 1, & \text{if } x \leq -1 \\ -2x, & \text{if } -1 < x < 1 \\ 2x, & \text{if } x \geq 1 \end{cases}$

8. $f(x) = \begin{cases} \frac{x}{x-1}, & \text{if } x \neq 1 \\ 0, & \text{if } x = 1 \end{cases}$ 9. $f(x) = \begin{cases} \frac{x}{x-1}, & \text{if } x < 0 \\ -1, & \text{if } x \geq 0 \end{cases}$

10. $f(x) = \begin{cases} x + 1, & \text{if } x \geq 1 \\ x^2 + 1, & \text{if } x < 1 \end{cases}$ 11. $f(x) = \begin{cases} x - 1, & \text{if } x \leq 2 \\ x^2 + 1, & \text{if } x > 2 \end{cases}$

12. $f(x) = \begin{cases} x^{10} - 1, & \text{if } x \leq 1 \\ x^2, & \text{if } x > 1 \end{cases}$

13. Is the function defined by

$$f(x) = \begin{cases} x + 5, & \text{if } x \leq 1 \\ x - 5, & \text{if } x > 1 \end{cases}$$

a continuous function

Discuss the continuity of the function f , where f is defined by

$$14. f(x) = \begin{cases} 1, & \text{if } 0 \leq x < 1 \\ 2, & \text{if } 1 < x < 2 \\ 3, & \text{if } 2 \leq x \leq 3 \end{cases} \quad 15. f(x) = \begin{cases} 2x, & \text{if } x < 0 \\ 0, & \text{if } 0 \leq x \leq 1 \\ x, & \text{if } x > 1 \end{cases}$$

$$16. f(x) = \begin{cases} -2, & \text{if } x \leq -1 \\ 2x, & \text{if } -1 < x \leq 1 \\ 2, & \text{if } x > 1 \end{cases}$$

17. Find the relationship between a and b so that the function f defined by

$$f(x) = \begin{cases} ax + 1, & \text{if } x \leq 1 \\ bx + 1, & \text{if } x > 1 \end{cases}$$

is continuous at $x = 1$.

18. For what value of λ is the function defined by

$$f(x) = \begin{cases} \lambda(x^2 - 2x), & \text{if } x \leq 0 \\ x + 1, & \text{if } x > 0 \end{cases}$$

continuous at $x = 0$. What about continuity at $x = 1$?

19. Show that the function defined by $g(x) = x - [x]$ is discontinuous at all integral points. Here $[x]$ denotes the greatest integer less than or equal to x .

20. Is the function defined by $f(x) = x^2 - \sin x$ continuous at $x = \pi$?

21. Discuss the continuity of the following functions

(a) $f(x) = \sin x \cos x$ (b) $f(x) = \sin x - \cos x$

(c) $f(x) = \sin x \cdot \cos x$

22. Discuss the continuity of the cosine, cosecant, secant and cotangent functions.

23. Find all points of discontinuity of f , where

$$f(x) = \begin{cases} \frac{\sin x}{x}, & \text{if } x < 0 \\ x + 1, & \text{if } x \geq 0 \end{cases}$$

24. Determine if f defined by

$$f(x) = \begin{cases} x^2 \sin \frac{1}{x}, & \text{if } x \neq 0 \\ 0, & \text{if } x = 0 \end{cases}$$

is a continuous function

25. Examine the continuity of f , where f is defined by

$$f(x) = \begin{cases} \sin x - \cos x, & \text{if } x \neq 0 \\ -1, & \text{if } x = 0 \end{cases}$$

Find the values of k so that the function f is continuous at the indicated point in exercises 26 to 30.

$$26. f(x) = \begin{cases} \frac{k \cos x}{\pi - 2x}, & \text{if } x \neq \frac{\pi}{2} \\ , & \text{if } x = \frac{\pi}{2} \end{cases} \quad \text{at } x = \frac{\pi}{2}$$

$$27. f(x) = \begin{cases} kx^2, & \text{if } x \leq 2 \\ , & \text{if } x > 2 \end{cases} \quad \text{at } x = 2$$

$$28. f(x) = \begin{cases} kx + 1, & \text{if } x \leq \pi \\ \cos x, & \text{if } x > \pi \end{cases} \quad \text{at } x = \pi$$

$$29. f(x) = \begin{cases} kx + 1, & \text{if } x \leq 5 \\ 5x, & \text{if } x > 5 \end{cases} \quad \text{at } x = 5$$

30. Find the values of a and b such that the function defined by

$$f(x) = \begin{cases} 5, & \text{if } x \leq 2 \\ ax + b, & \text{if } 2 < x < 10 \\ 21, & \text{if } x \geq 10 \end{cases}$$

is a continuous function.

31. Show that the function defined by $f(x) = \cos(x^2)$ is a continuous function.

32. Show that the function defined by $f(x) = \cos x$ is a continuous function.

33. Examine that $\sin x$ is a continuous function.

34. Find all the points of discontinuity of f defined by $f(x) = x - x^{-1}$.

5.3. Differentiability

Recall the following facts from previous class. We had defined the derivative of a real function as follows

Suppose f is a real function and c is a point in its domain. The derivative of f at c is defined by

$$\lim_{h \rightarrow 0} \frac{f(c+h) - f(c)}{h}$$

provided this limit exists. erivative of f at c is denoted by $f'(c)$ or $\frac{d}{dx}(f(x))_c$. The function defined by

$$f'(x) = \lim_{h \rightarrow 0} \frac{f(x+h) - f(x)}{h}$$

wherever the limit exists is defined to be the derivative of f . The derivative of f is denoted by $f'(x)$ or $\frac{d}{dx}(f(x))$ or if $y = f(x)$ by $\frac{dy}{dx}$ or y' . The process of finding derivative of a function is called differentiation. We also use the phrase *differentiate $f(x)$ with respect to x* to mean *find $f'(x)$* .

The following rules were established as a part of algebra of derivatives

- (1) $(u \pm v)' = u' \pm v'$
- (2) $(uv)' = u'v + uv'$ (eibnit or product rule)
- (3) $\left(\frac{u}{v}\right)' = \frac{u'v - uv'}{v^2}$, wherever $v \neq 0$ (uotient rule).

The following table gives a list of derivatives of certain standard functions

Table 5.3

$f(x)$	x^n	$\sin x$	$\cos x$	$\tan x$
$f'(x)$	nx^{n-1}	$\cos x$	$-\sin x$	$\sec^2 x$

Whenever we defined derivative, we had put a caution *provided the limit exists*. ow the natural question is what if it doesn't The question is quite pertinent and so is

its answer. If $\lim_{h \rightarrow 0} \frac{f(c+h) - f(c)}{h}$ does not exist, we say that f is not differentiable at c .

In other words, we say that a function f is differentiable at a point c in its domain if both

$\lim_{h \rightarrow 0^-} \frac{f(c+h) - f(c)}{h}$ and $\lim_{h \rightarrow 0^+} \frac{f(c+h) - f(c)}{h}$ are finite and equal. A function is said

to be differentiable in an interval $[a, b]$ if it is differentiable at every point of $[a, b]$. As in case of continuity, at the end points a and b , we take the right hand limit and left hand limit, which are nothing but left hand derivative and right hand derivative of the function at a and b respectively. imilarly, a function is said to be differentiable in an interval (a, b) if it is differentiable at every point of (a, b) .

Theorem 3 If a function f is differentiable at a point c , then it is also continuous at that point.

Proof Since f is differentiable at c , we have

$$\lim_{x \rightarrow c} \frac{f(x) - f(c)}{x - c} = f'(c)$$

but for $x \neq c$, we have

$$f(x) - f(c) = \frac{f(x) - f(c)}{x - c} \cdot (x - c)$$

Therefore
$$\lim_{x \rightarrow c} (f(x) - f(c)) = \lim_{x \rightarrow c} \left[\frac{f(x) - f(c)}{x - c} \cdot (x - c) \right]$$

or
$$\lim_{x \rightarrow c} (f(x) - f(c)) = \lim_{x \rightarrow c} \left[\frac{f(x) - f(c)}{x - c} \right] \cdot \lim_{x \rightarrow c} (x - c)$$

$$= f'(c) \cdot 0 = 0$$

or
$$\lim_{x \rightarrow c} f(x) = f(c)$$

hence f is continuous at $x = c$.

Corollary 1 Every differentiable function is continuous.

We remark that the converse of the above statement is not true. Indeed we have seen that the function defined by $f(x) = |x|$ is a continuous function. Consider the left hand limit

$$\lim_{h \rightarrow 0^-} \frac{f(0+h) - f(0)}{h} = \frac{-h}{h} = -1$$

The right hand limit

$$\lim_{h \rightarrow 0^+} \frac{f(0+h) - f(0)}{h} = \frac{h}{h} = 1$$

Since the above left and right hand limits at 0 are not equal, $\lim_{h \rightarrow 0} \frac{f(0+h) - f(0)}{h}$ does not exist and hence f is not differentiable at 0. Thus f is not a differentiable function.

5.3.1 Derivatives of composite functions

To study derivative of composite functions, we start with an illustrative example. Say, we want to find the derivative of f , where

$$f(x) = (2x - 1)$$

One way is to expand $(2x + 1)^{100}$ using binomial theorem and find the derivative as a polynomial function as illustrated below.

$$\begin{aligned}\frac{d}{dx} f(x) &= \frac{d}{dx} [(2x+1)^{100}] \\ &= \frac{d}{dx} (100(2x+1)^{99} \cdot 2) \\ &= 200(2x+1)^{99}\end{aligned}$$

Now, observe that

$$f(x) = (h \circ g)(x)$$

where $g(x) = 2x + 1$ and $h(x) = x^{100}$. Let $t = g(x) = 2x + 1$. Then $f(x) = h(t) = t^{100}$. Thus

$$\frac{df}{dx} = \frac{d}{dx} (2x + 1)^{100} = \frac{d}{dt} t^{100} \cdot \frac{dt}{dx} = 100t^{99} \cdot 2 = \frac{dh}{dt} \cdot \frac{dt}{dx}$$

The advantage with such observation is that it simplifies the calculation in finding the derivative of, say, $(2x + 1)^{100}$. We may formalise this observation in the following theorem called the chain rule.

Theorem 4 (Chain Rule) Let f be a real valued function which is a composite of two functions u and v i.e., $f = v \circ u$. Suppose $t = u(x)$ and if both $\frac{dv}{dt}$ and $\frac{du}{dx}$ exist, we have

$$\frac{df}{dx} = \frac{dv}{dt} \cdot \frac{du}{dx}$$

We skip the proof of this theorem. Chain rule may be extended as follows. Suppose f is a real valued function which is a composite of three functions u , v and w i.e.,

$$f = (w \circ v) \circ u. \text{ If } t = v(x) \text{ and } s = u(t), \text{ then}$$

$$\frac{df}{dx} = \frac{d(w \circ v)}{dt} \cdot \frac{dt}{dx} = \frac{dw}{ds} \cdot \frac{ds}{dt} \cdot \frac{dt}{dx}$$

provided all the derivatives in the statement exist. Reader is invited to formulate chain rule for composite of more functions.

Example 21 Find the derivative of the function given by $f(x) = \sin(x^2)$.

Solution Observe that the given function is a composite of two functions. Indeed, if $t = u(x) = x^2$ and $v(t) = \sin t$, then

$$f(x) = (v \circ u)(x) = v(u(x)) = v(x^2) = \sin x^2$$

Let $t = u(x) = x^2$. Observe that $\frac{dv}{dt} = \cos t$ and $\frac{dt}{dx} = 2x$ exist. Hence, by chain rule

$$\frac{df}{dx} = \frac{dv}{dt} \cdot \frac{dt}{dx} = \cos t \cdot 2x$$

It is normal practice to express the final result only in terms of x . Thus

$$\frac{df}{dx} = \cos t \cdot 2x = 2x \cos x^2$$

Alternatively, We can also directly proceed as follows

$$\begin{aligned} y = \sin(x^2) &\Rightarrow \frac{dy}{dx} = \frac{d}{dx}(\sin x^2) \\ &= \cos x^2 \cdot \frac{d}{dx}(x^2) = 2x \cos x^2 \end{aligned}$$

Example 22 Find the derivative of $\tan(2x)$.

Solution Let $f(x) = \tan(2x)$, $u(x) = 2x$ and $v(t) = \tan t$. Then

$$(v \circ u)(x) = v(u(x)) = v(2x) = \tan(2x) = f(x)$$

Thus f is a composite of two functions. Let $t = u(x) = 2x$. Then $\frac{dv}{dt} = \sec^2 t$ and

$\frac{dt}{dx} = 2$ exist. Hence, by chain rule

$$\frac{df}{dx} = \frac{dv}{dt} \cdot \frac{dt}{dx} = 2 \sec^2(2x)$$

Example 23 Differentiate $\sin(\cos(x^2))$ with respect to x .

Solution The function $f(x) = \sin(\cos(x^2))$ is a composition $f(x) = (w \circ v \circ u)(x)$ of the three functions u , v and w , where $u(x) = x^2$, $v(t) = \cos t$ and $w(s) = \sin s$. Let

$t = u(x) = x^2$ and $s = v(t) = \cos t$. Observe that $\frac{dw}{ds} = \cos s$, $\frac{ds}{dt} = -\sin t$ and $\frac{dt}{dx} = 2x$

exist for all real x . Hence by a generalisation of chain rule, we have

$$\frac{df}{dx} = \frac{dw}{ds} \cdot \frac{ds}{dt} \cdot \frac{dt}{dx} = (\cos s) \cdot (-\sin t) \cdot (2x) = -2x \sin x^2 \cdot \cos(\cos x^2)$$

Alternatively, we can proceed as follows

$$y = \sin(\cos x^2)$$

$$\begin{aligned} \text{Therefore } \frac{dy}{dx} &= \frac{d}{dx} \sin(\cos x^2) = \cos(\cos x^2) \frac{d}{dx}(\cos x^2) \\ &= \cos(\cos x^2) (-\sin x^2) \frac{d}{dx}(x^2) \\ &= -\sin x^2 \cos(\cos x^2) (2x) \\ &= -2x \sin x^2 \cos(\cos x^2) \end{aligned}$$

EXERCISE 5.2

ifferentiate the functions with respect to x in exercises 1 to .

1. $\sin(x^2 - 5)$ 2. $\cos(\sin x)$ 3. $\sin(ax + b)$
4. $\sec(\tan(\sqrt{x}))$ 5. $\frac{\sin(ax+b)}{\cos(cx+d)}$ 6. $\cos x \cdot \sin^2(x^5)$
7. $2\sqrt{\cot(x^2)}$ 8. $\cos(\sqrt{x})$
9. prove that the function f given by

$$f(x) = x - 1, \quad x \in \mathbf{R}$$

is not differentiable at $x = 1$.

10. prove that the greatest integer function defined by

$$f(x) = x, \quad 0 \leq x < 1$$

is not differentiable at $x = 1$ and $x = 2$.

5.3.2 Derivatives of implicit functions

until now we have been differentiating various functions given in the form $y = f(x)$. But it is not necessary that functions are always expressed in this form. For example, consider one of the following relationships between x and y

$$x - y - \pi = 0$$

$$x \sin xy - y = 0$$

In the first case, we can *solve for* y and rewrite the relationship as $y = x - \pi$. In the second case, it does not seem that there is an easy way to *solve for* y . nevertheless, there is no doubt about the dependence of y on x in either of the cases. When a relationship between x and y is expressed in a way that it is easy to *solve for* y and write $y = f(x)$, we say that y is given as an *explicit function* of x . In the latter case it

is implicit that y is a function of x and we say that the relationship of the second type, above, gives function *implicitly*. In this subsection, we learn to differentiate implicit functions.

Example 24 Find $\frac{dy}{dx}$ if $x - y = \pi$.

Solution One way is to solve for y and rewrite the above as

$$y = x - \pi$$

ut then $\frac{dy}{dx} = 1$

Alternatively, *directly* differentiating the relationship w.r.t., x , we have

$$\frac{d}{dx}(x - y) = \frac{d\pi}{dx}$$

recall that $\frac{d\pi}{dx}$ means to differentiate the constant function taking value π everywhere w.r.t., x . Thus

$$\frac{d}{dx}(x) - \frac{d}{dx}(y) = 0$$

which implies that

$$\frac{dy}{dx} = \frac{dx}{dx} = 1$$

Example 25 Find $\frac{dy}{dx}$, if $y \sin y = \cos x$.

Solution We differentiate the relationship directly with respect to x , i.e.,

$$\frac{dy}{dx} + \frac{d}{dx}(\sin y) = \frac{d}{dx}(\cos x)$$

which implies using chain rule

$$\frac{dy}{dx} + \cos y \cdot \frac{dy}{dx} = -\sin x$$

This gives

$$\frac{dy}{dx} = -\frac{\sin x}{1 + \cos y}$$

where

$$y \neq (2n - 1)\pi$$

5.3.3 Derivatives of inverse trigonometric functions

We remark that inverse trigonometric functions are continuous functions, but we will not prove this. Now we use chain rule to find derivatives of these functions.

Example 26 Find the derivative of f given by $f(x) = \sin^{-1} x$ assuming it exists.

Solution Let $y = \sin^{-1} x$. Then, $x = \sin y$.
Differentiating both sides w.r.t. x , we get

$$1 = \cos y \frac{dy}{dx}$$

which implies that
$$\frac{dy}{dx} = \frac{1}{\cos y} = \frac{1}{\cos(\sin^{-1} x)}$$

Observe that this is defined only for $\cos y \neq 0$, i.e., $\sin^{-1} x \neq -\frac{\pi}{2}, \frac{\pi}{2}$, i.e., $x \neq -1, 1$,
i.e., $x \in (-1, 1)$.

To make this result a bit more attractive, we carry out the following manipulation.
Recall that for $x \in (-1, 1)$, $\sin(\sin^{-1} x) = x$ and hence

$$\cos^2 y = 1 - (\sin y)^2 = 1 - (\sin(\sin^{-1} x))^2 = 1 - x^2$$

Also, since $y \in \left(-\frac{\pi}{2}, \frac{\pi}{2}\right)$, $\cos y$ is positive and hence $\cos y = \sqrt{1 - x^2}$

Thus, for $x \in (-1, 1)$,

$$\frac{dy}{dx} = \frac{1}{\cos y} = \frac{1}{\sqrt{1 - x^2}}$$

Example 27 Find the derivative of f given by $f(x) = \tan^{-1} x$ assuming it exists.

Solution Let $y = \tan^{-1} x$. Then, $x = \tan y$.
Differentiating both sides w.r.t. x , we get

$$1 = \sec^2 y \frac{dy}{dx}$$

which implies that

$$\frac{dy}{dx} = \frac{1}{\sec^2 y} = \frac{1}{1 + \tan^2 y} = \frac{1}{1 + (\tan(\tan^{-1} x))^2} = \frac{1}{1 + x^2}$$

Finding of the derivatives of other inverse trigonometric functions is left as exercise. The following table gives the derivatives of the remaining inverse trigonometric functions (Table 5.)

Table 5.4

$f(x)$	$\cos^{-1}x$	$\cot^{-1}x$	$\sec^{-1}x$	$\operatorname{cosec}^{-1}x$
$f'(x)$	$\frac{-1}{\sqrt{1-x^2}}$	$\frac{-1}{1+x^2}$	$\frac{1}{x\sqrt{x^2-1}}$	$\frac{-1}{x\sqrt{x^2-1}}$
omain of f'	$(-1, 1)$	R	$(-\infty, -1) \cup (1, \infty)$	$(-\infty, -1) \cup (1, \infty)$

EXERCISE 5.3

Find $\frac{dy}{dx}$ in the following

1. $2x + y = \sin x$
2. $2x + y = \sin y$
3. $ax + by^2 = \cos y$
4. $xy + y^2 = \tan x$
5. $x^2 + xy - y^2 = 100$
6. $x + x^2y - xy^2 = y = 1$
7. $\sin^2 y + \cos xy = \kappa$
8. $\sin^2 x + \cos^2 y = 1$
9. $y = \sin^{-1} \left(\frac{2x}{1+x^2} \right)$
10. $y = \tan^{-1} \left(\frac{x-x}{1-x^2} \right), -\frac{1}{\sqrt{e}} < x < \frac{1}{\sqrt{e}}$
11. $y = \cos^{-1} \left(\frac{1-x^2}{1+x^2} \right), 0 < x < 1$
12. $y = \sin^{-1} \left(\frac{1-x^2}{1+x^2} \right), 0 < x < 1$
13. $y = \cos^{-1} \left(\frac{2x}{1+x^2} \right), -1 < x < 1$
14. $y = \sin^{-1} (2x\sqrt{1-x^2}), -\frac{1}{\sqrt{2}} < x < \frac{1}{\sqrt{2}}$
15. $y = \sec^{-1} \left(\frac{1}{2x^2-1} \right), 0 < x < \frac{1}{\sqrt{2}}$

5.4 Exponential and Logarithmic Functions

Till now we have learnt some aspects of different classes of functions like polynomial functions, rational functions and trigonometric functions. In this section, we shall learn about a new class of (related) functions called exponential functions and logarithmic functions. It needs to be emphasised that many statements made in this section are motivational and precise proofs of these are well beyond the scope of this text.

The Fig 5. gives a sketch of $y = f_1(x) = x$, $y = f_2(x) = x^2$, $y = f_3(x) = x^3$ and $y = f_n(x) = x^n$. Observe that the curves get steeper as the power of x increases. The steeper the curve, faster is the rate of growth. What this means is that for a fixed

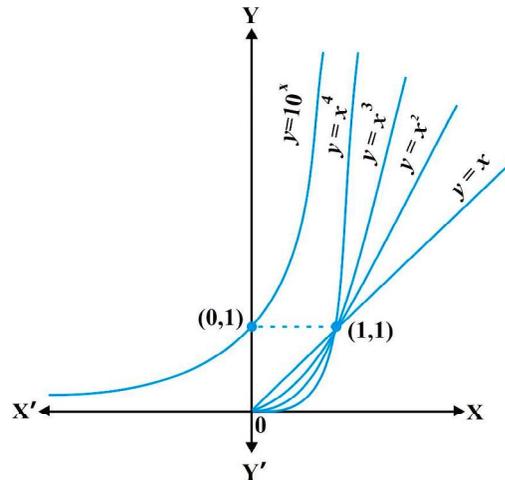


Fig 5.9

increment in the value of x (> 1), the increment in the value of $y = f_n(x)$ increases as n increases for $n = 1, 2, 3, \dots$. It is conceivable that such a statement is true for all positive values of n , where $f_n(x) = x^n$. Essentially, this means that the graph of $y = f_n(x)$ leans more towards the y -axis as n increases. For example, consider $f_{10}(x) = x^{10}$ and $f_{15}(x) = x^{15}$. If x increases from 1 to 2, f_{10} increases from 1 to 2^{10} whereas f_{15} increases from 1 to 2^{15} . Thus, for the same increment in x , f_{15} grows faster than f_{10} .

The upshot of the above discussion is that the growth of polynomial functions is dependent on the degree of the polynomial function – higher the degree, greater is the growth. The next natural question is Is there a function which grows faster than any polynomial function. The answer is in affirmative and an example of such a function is

$$y = f(x) = 10^x.$$

Our claim is that this function f grows faster than $f_n(x) = x^n$ for any positive integer n . For example, we can prove that 10^x grows faster than $f_{100}(x) = x^{100}$. For large values of x like $x = 10$, note that $f_{100}(10) = (10)^{100} = 10^{100}$ whereas $f(10) = 10^{10} = 10^{1000}$. Clearly $f(x)$ is much greater than $f_{100}(x)$. It is not difficult to prove that for all $x > 10$, $f(x) > f_{100}(x)$. But we will not attempt to give a proof of this here. Similarly, by choosing large values of x , one can verify that $f(x)$ grows faster than $f_n(x)$ for any positive integer n .

Definition 3 The exponential function with positive base $b \neq 1$ is the function

$$y = f(x) = b^x$$

The graph of $y = 10^x$ is given in the Fig 5..

It is advised that the reader plots this graph for particular values of b like 2, and . Following are some of the salient features of the exponential functions

- (1) Domain of the exponential function is \mathbf{R} , the set of all real numbers.
- (2) Range of the exponential function is the set of all positive real numbers.
- (3) The point $(0, 1)$ is always on the graph of the exponential function (this is a restatement of the fact that $b^0 = 1$ for any real $b \neq 1$).
- (4) Exponential function is ever increasing i.e., as we move from left to right, the graph rises above.
- (5) For very large negative values of x , the exponential function is very close to 0. In other words, in the second quadrant, the graph approaches x -axis (but never meets it).

Exponential function with base 10 is called the *common exponential function*. In the Appendix A.1. of Class XI, it was observed that the sum of the series

$$1 + \frac{1}{12} + \frac{1}{12^2} + \dots$$

is a number between 2 and and is denoted by e . Using this e as the base we obtain an extremely important exponential function $y = e^x$.

This is called *natural exponential function*.

It would be interesting to know if the inverse of the exponential function exists and has nice interpretation. This search motivates the following definition.

Definition 4 Let $b \neq 1$ be a real number. Then we say logarithm of a to base b is x if $b^x = a$.

Logarithm of a to base b is denoted by $\log_b a$. Thus $\log_b a = x$ if $b^x = a$. Let us work with a few explicit examples to get a feel for this. We know $2^4 = 16$. In terms of logarithms, we may rewrite this as $\log_2 16 = 4$. Similarly, $10^4 = 10000$ is equivalent to saying $\log_{10} 10000 = 4$. Also, $25 = 5^2 = 5^2$ is equivalent to saying $\log_5 25 = 2$ or $\log_{25} 25 = 1$.

On a slightly more mature note, fixing a base $b \neq 1$, we may look at logarithm as a function from positive real numbers to all real numbers. This function, called the *logarithmic function*, is defined by

$$\begin{aligned} \log_b \mathbf{R} &\rightarrow \mathbf{R} \\ x &\rightarrow \log_b x = y \quad \text{if } b^y = x \end{aligned}$$

As before if the base $b = 10$, we say it is *common logarithms* and if $b = e$, then we say it is *natural logarithms*. Often natural logarithm is denoted by \ln . In this chapter, $\log x$ denotes the logarithm function to base e , i.e., $\ln x$ will be written as simply $\log x$. The Fig 5.10 gives the plots of logarithm function to base 2, e and 10.

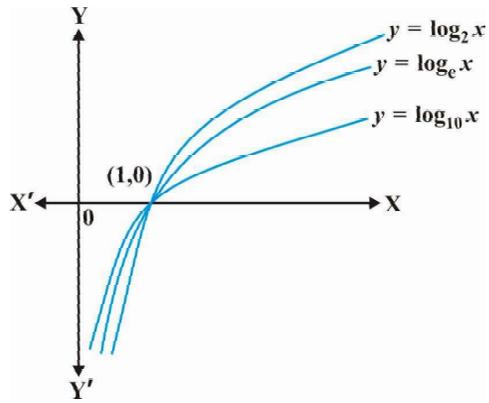


Fig 5.10

Some of the important observations about the logarithm function to any base $b > 1$ are listed below

- (1) We cannot make a meaningful definition of logarithm of non-positive numbers and hence the domain of log function is \mathbf{R}^+ .
- (2) The range of log function is the set of all real numbers.
- (3) The point $(1, 0)$ is always on the graph of the log function.
- (4) The log function is ever increasing, i.e., as we move from left to right the graph rises above.
- (5) For x very near to zero, the value of $\log x$ can be made lesser than any given real number. In other words in the fourth quadrant the graph approaches y -axis (but never meets it).
- (6) Fig 5.11 gives the plot of $y = e^x$ and $y = \ln x$. It is of interest to observe that the two curves are the mirror images of each other reflected in the line $y = x$.

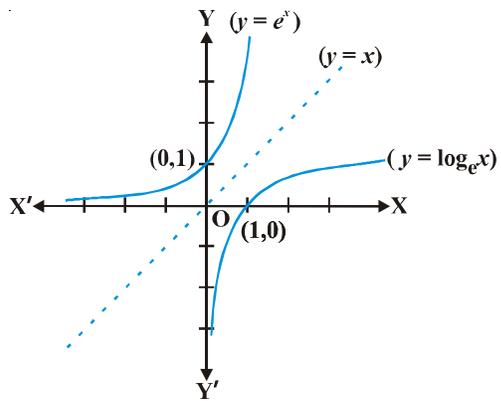


Fig 5.11

Two properties of log functions are proved below

- (1) There is a standard change of base rule to obtain $\log_a p$ in terms of $\log_b p$. Let $\log_a p = \alpha$, $\log_b p = \beta$ and $\log_b a = \gamma$. This means $a^\alpha = p$, $b^\beta = p$ and $b^\gamma = a$. Substituting the third equation in the first one, we have

$$(b^\gamma)^\alpha = b^{\gamma\alpha} = p$$

Using this in the second equation, we get

$$b^\beta = p = b^{\gamma\alpha}$$

which implies $\beta = \alpha\gamma$ or $\alpha = \frac{\beta}{\gamma}$. ut then

$$\log_a p = \frac{\log_b p}{\log_b a}$$

- (2) Another interesting property of the log function is its effect on products. et $\log_b pq = \alpha$. Then $b^\alpha = pq$. If $\log_b p = \beta$ and $\log_b q = \gamma$, then $b^\beta = p$ and $b^\gamma = q$. ut then $b^\alpha = pq = b^\beta b^\gamma = b^{\beta + \gamma}$ which implies $\alpha = \beta + \gamma$, i.e.,

$$\log_b pq = \log_b p + \log_b q$$

A particularly interesting and important consequence of this is when $p = q$. In this case the above may be rewritten as

$$\log_b p^2 = \log_b p + \log_b p = 2 \log_b p$$

An easy generalisation of this (left as an exercise) is

$$\log_b p^n = n \log_b p$$

for any positive integer n . In fact this is true for any real number n , but we will not attempt to prove this. On the similar lines the reader is invited to verify

$$\log_b \frac{x}{y} = \log_b x - \log_b y$$

Example 28 Is it true that $x = e^{\log x}$ for all real x

Solution First, observe that the domain of log function is set of all positive real numbers. o the above equation is not true for non-positive real numbers. ow, let $y = e^{\log x}$. If $y > 0$, we may take logarithm which gives us $\log y = \log(e^{\log x}) = \log x \cdot \log e = \log x$. Thus $y = x$. ence $x = e^{\log x}$ is true only for positive values of x .

One of the striking properties of the natural exponential function in differential calculus is that it doesn't change during the process of differentiation. This is captured in the following theorem whose proof we skip.

Theorem 5*

- (1) The derivative of e^x w.r.t., x is e^x i.e., $\frac{d}{dx}(e^x) = e^x$.
- (2) The derivative of $\log x$ w.r.t., x is $\frac{1}{x}$ i.e., $\frac{d}{dx}(\log x) = \frac{1}{x}$.

* Please see supplementary material on Page 286.

Example 29 Differentiate the following w.r.t. x

- (i) e^{-x} (ii) $\sin(\log x), x > 0$ (iii) $\cos^{-1}(e^x)$ (iv) $e^{\cos x}$

Solution

- (i) Let $y = e^{-x}$. Using chain rule, we have

$$\frac{dy}{dx} = e^{-x} \cdot \frac{d}{dx}(-x) = -e^{-x}$$

- (ii) Let $y = \sin(\log x)$. Using chain rule, we have

$$\frac{dy}{dx} = \cos(\log x) \cdot \frac{d}{dx}(\log x) = \frac{\cos(\log x)}{x}$$

- (iii) Let $y = \cos^{-1}(e^x)$. Using chain rule, we have

$$\frac{dy}{dx} = \frac{-1}{\sqrt{1-(e^x)^2}} \cdot \frac{d}{dx}(e^x) = \frac{-e^x}{\sqrt{1-e^{2x}}}$$

- (iv) Let $y = e^{\cos x}$. Using chain rule, we have

$$\frac{dy}{dx} = e^{\cos x} \cdot (-\sin x) = -(\sin x) e^{\cos x}$$

EXERCISE 5.4

Differentiate the following w.r.t. x

1. $\frac{e^x}{\sin x}$ 2. $e^{\sin^{-1} x}$ 3. e^x
4. $\sin(\tan^{-1} e^{-x})$ 5. $\log(\cos e^x)$ 6. $e^x + e^{x^2} + \dots + e^{x^5}$
7. $\sqrt{e^{\sqrt{x}}}, x > 0$ 8. $\log(\log x), x > 1$ 9. $\frac{\cos x}{\log x}, x > 0$
10. $\cos(\log x - e^x), x > 0$

5.5. Logarithmic Differentiation

In this section, we will learn to differentiate certain special class of functions given in the form

$$y = f(x) = u(x)^{v(x)}$$

By taking logarithm (to base e) the above may be rewritten as

$$\log y = v(x) \log u(x)$$

using chain rule we may differentiate this to get

$$\frac{1}{y} \cdot \frac{dy}{dx} = v(x) \cdot \frac{1}{u(x)} \cdot u'(x) + v'(x) \cdot \log u(x)$$

which implies that

$$\frac{dy}{dx} = y \left[\frac{v(x)}{u(x)} \cdot u'(x) + v'(x) \cdot \log[u(x)] \right]$$

The main point to be noted in this method is that $f(x)$ and $u(x)$ must always be positive as otherwise their logarithms are not defined. This process of differentiation is known as *logarithms differentiation* and is illustrated by the following examples

Example 30 Differentiate $\sqrt{\frac{(x-1)(x^2+5)}{5x^2+x+1}}$ w.r.t. x .

Solution Let $y = \sqrt{\frac{(x-1)(x^2+5)}{5x^2+x+1}}$

Taking logarithm on both sides, we have

$$\log y = \frac{1}{2} \log(x-1) + \log(x^2+5) - \log(5x^2+x+1)$$

Now, differentiating both sides w.r.t. x , we get

$$\frac{1}{y} \cdot \frac{dy}{dx} = \frac{1}{2} \left[\frac{1}{(x-1)} + \frac{2x}{x^2+5} - \frac{x+1}{x^2+x+1} \right]$$

or

$$\begin{aligned} \frac{dy}{dx} &= \frac{y}{2} \left[\frac{1}{(x-1)} + \frac{2x}{x^2+5} - \frac{x+1}{x^2+x+1} \right] \\ &= \frac{1}{2} \sqrt{\frac{(x-1)(x^2+5)}{5x^2+x+1}} \left[\frac{1}{(x-1)} + \frac{2x}{x^2+5} - \frac{x+1}{x^2+x+1} \right] \end{aligned}$$

Example 31 Differentiate a^x w.r.t. x , where a is a positive constant.

Solution Let $y = a^x$. Then

$$\log y = x \log a$$

Differentiating both sides w.r.t. x , we have

$$\frac{1}{y} \frac{dy}{dx} = \log a$$

or
$$\frac{dy}{dx} = y \log a$$

Thus
$$\frac{d}{dx}(a^x) = a^x \log a$$

Alternatively
$$\begin{aligned} \frac{d}{dx}(a^x) &= \frac{d}{dx}(e^{x \log a}) = e^{x \log a} \frac{d}{dx}(x \log a) \\ &= e^{x \log a} \cdot \log a = a^x \log a. \end{aligned}$$

Example 32 Differentiate $x^{\sin x}$, $x > 0$ w.r.t. x .

Solution Let $y = x^{\sin x}$. Taking logarithm on both sides, we have

$$\log y = \sin x \log x$$

Therefore
$$\frac{1}{y} \cdot \frac{dy}{dx} = \sin x \frac{d}{dx}(\log x) + \log x \frac{d}{dx}(\sin x)$$

or
$$\frac{1}{y} \frac{dy}{dx} = (\sin x) \frac{1}{x} + \log x \cos x$$

or
$$\begin{aligned} \frac{dy}{dx} &= y \left[\frac{\sin x}{x} + \cos x \log x \right] \\ &= x^{\sin x} \left[\frac{\sin x}{x} + \cos x \log x \right] \\ &= x^{\sin x - 1} \cdot \sin x + x^{\sin x} \cdot \cos x \log x \end{aligned}$$

Example 33 Find $\frac{dy}{dx}$, if $y^x = x^y = x^x = a^b$.

Solution Given that $y^x = x^y = x^x = a^b$.

Putting $u = y^x$, $v = x^y$ and $w = x^x$, we get $u = v = w = a^b$

Therefore
$$\frac{du}{dx} + \frac{dv}{dx} + \frac{dw}{dx} = 0 \quad \dots (1)$$

Now, $u = y^x$. Taking logarithm on both sides, we have

$$\log u = x \log y$$

Differentiating both sides w.r.t. x , we have

$$\begin{aligned} \frac{1}{u} \cdot \frac{du}{dx} &= x \frac{d}{dx}(\log y) + \log y \frac{d}{dx}(x) \\ &= x \frac{1}{y} \cdot \frac{dy}{dx} + \log y \cdot 1 \end{aligned}$$

o

$$\frac{du}{dx} = u \left(\frac{x}{y} \frac{dy}{dx} + \log y \right) = y^x \left[\frac{x}{y} \frac{dy}{dx} + \log y \right] \quad \dots (2)$$

Also $v = x^y$

Taking logarithm on both sides, we have

$$\log v = y \log x$$

ifferentiating both sides w.r.t. x , we have

$$\begin{aligned} \frac{1}{v} \cdot \frac{dv}{dx} &= y \frac{d}{dx}(\log x) + \log x \frac{dy}{dx} \\ &= y \cdot \frac{1}{x} + \log x \cdot \frac{dy}{dx} \end{aligned}$$

o

$$\begin{aligned} \frac{dv}{dx} &= v \left[\frac{y}{x} + \log x \frac{dy}{dx} \right] \\ &= x^y \left[\frac{y}{x} + \log x \frac{dy}{dx} \right] \quad \dots (3) \end{aligned}$$

Again

$$w = x^x$$

Taking logarithm on both sides, we have

$$\log w = x \log x.$$

ifferentiating both sides w.r.t. x , we have

$$\begin{aligned} \frac{1}{w} \cdot \frac{dw}{dx} &= x \frac{d}{dx}(\log x) + \log x \cdot \frac{d}{dx}(x) \\ &= x \cdot \frac{1}{x} + \log x \cdot 1 \end{aligned}$$

i.e.

$$\begin{aligned} \frac{dw}{dx} &= w(1 + \log x) \\ &= x^x(1 + \log x) \quad \dots (4) \end{aligned}$$

From (1), (2), (3), (4), we have

$$y^x \left(\frac{x}{y} \frac{dy}{dx} + \log y \right) + x^y \left(\frac{y}{x} + \log x \frac{dy}{dx} \right) - x^x (1 + \log x) = 0$$

or $(x \cdot y^{x-1} - x^y \cdot \log x) \frac{dy}{dx} = -x^x (1 + \log x) - y \cdot x^{y-1} - y^x \log y$

Therefore $\frac{dy}{dx} = \frac{-\log x \cdot y + y \cdot x^{y-1} - (x^x \log x) - x}{x \cdot y^{x-1} + x^y \log x}$

EXERCISE 5.5

differentiate the functions given in exercises 1 to 11 w.r.t. x .

- | | |
|---|--|
| 1. $\cos x \cdot \cos 2x \cdot \cos x$ | 2. $\sqrt{\frac{(x-1)(x-2)}{(x-3)(x-4)(x-5)}}$ |
| 3. $(\log x)^{\cos x}$ | 4. $x^x - 2^{\sin x}$ |
| 5. $(x+1)^2 \cdot (x-1) \cdot (x-5)$ | 6. $\left(x + \frac{1}{x}\right)^x + x^{\left(1 + \frac{1}{x}\right)}$ |
| 7. $(\log x)^x \cdot x^{\log x}$ | 8. $(\sin x)^x \sin^{-1} \sqrt{x}$ |
| 9. $x^{\sin x} (\sin x)^{\cos x}$ | 10. $x^{-x \cos x} + \frac{x^2 + 1}{x^2 - 1}$ |
| 11. $(x \cos x)^x \cdot (x \sin x)^{\frac{1}{x}}$ | |

Find $\frac{dy}{dx}$ of the functions given in exercises 12 to 15.

- | | |
|---|----------------------|
| 12. $x^y \cdot y^x = 1$ | 13. $y^x = x^y$ |
| 14. $(\cos x)^y = (\cos y)^x$ | 15. $xy = e^{(x-y)}$ |
| 16. Find the derivative of the function given by $f(x) = (1-x)(1-x^2)(1-x)(1-x)$ and hence find $f'(1)$. | |
| 17. Differentiate $(x^2 - 5x)(x - x)$ in three ways mentioned below | |
| (i) by using product rule | |
| (ii) by expanding the product to obtain a single polynomial. | |
| (iii) by logarithmic differentiation. | |
| Do they all give the same answer | |

18. If u , v and w are functions of x , then show that

$$\frac{d}{dx} (u \cdot v \cdot w) = \frac{du}{dx} \cdot v \cdot w + u \cdot \frac{dv}{dx} \cdot w + u \cdot v \cdot \frac{dw}{dx}$$

in two ways - first by repeated application of product rule, second by logarithmic differentiation.

5.6 Derivatives of Functions in Parametric Forms

ometimes the relation between two variables is neither explicit nor implicit, but some link of a third variable with each of the two variables, separately, establishes a relation between the first two variables. In such a situation, we say that the relation between them is expressed via a third variable. The third variable is called the parameter. More precisely, a relation expressed between two variables x and y in the form $x = f(t)$, $y = g(t)$ is said to be parametric form with t as a parameter.

In order to find derivative of function in such form, we have by chain rule.

$$\frac{dy}{dt} = \frac{dy}{dx} \cdot \frac{dx}{dt}$$

or
$$\frac{dy}{dx} = \frac{\frac{dy}{dt}}{\frac{dx}{dt}} \left(\text{whenever } \frac{dx}{dt} \neq 0 \right)$$

Thus
$$\frac{dy}{dx} = \frac{g'(t)}{f'(t)} \left(\text{as } \frac{dy}{dt} = g'(t) \text{ and } \frac{dx}{dt} = f'(t) \right) \text{ provided } f'(t) \neq 0$$

Example 34 Find $\frac{dy}{dx}$, if $x = a \cos \theta$, $y = a \sin \theta$.

Solution Given that

$$x = a \cos \theta, y = a \sin \theta$$

Therefore
$$\frac{dx}{d\theta} = -a \sin \theta, \frac{dy}{d\theta} = a \cos \theta$$

ence
$$\frac{dy}{dx} = \frac{\frac{dy}{d\theta}}{\frac{dx}{d\theta}} = \frac{a \cos \theta}{-a \sin \theta} = -\cot \theta$$

Example 35 Find $\frac{dy}{dx}$, if $x = at^2$, $y = 2at$.

Solution Given that $x = at^2$, $y = 2at$

$$\text{or} \quad \frac{dx}{dt} = 2at \quad \text{and} \quad \frac{dy}{dt} = 2a$$

Therefore

$$\frac{dy}{dx} = \frac{\frac{dy}{dt}}{\frac{dx}{dt}} = \frac{2a}{2at} = \frac{1}{t}$$

Example 36 Find $\frac{dy}{dx}$, if $x = a(\theta - \sin \theta)$, $y = a(1 - \cos \theta)$.

Solution We have $\frac{dx}{d\theta} = a(1 - \cos \theta)$, $\frac{dy}{d\theta} = a(\sin \theta)$

Therefore

$$\frac{dy}{dx} = \frac{\frac{dy}{d\theta}}{\frac{dx}{d\theta}} = \frac{a \sin \theta}{a(1 + \cos \theta)} = \tan \frac{\theta}{2}$$

 **Note** It may be noted here that $\frac{dy}{dx}$ is expressed in terms of parameter only without directly involving the main variables x and y .

Example 37 Find $\frac{dy}{dx}$, if $x^{\frac{2}{3}} + y^{\frac{2}{3}} = a^{\frac{2}{3}}$.

Solution Let $x = a \cos^3 \theta$, $y = a \sin^3 \theta$. Then

$$\begin{aligned} x^{\frac{2}{3}} + y^{\frac{2}{3}} &= (a \cos^3 \theta)^{\frac{2}{3}} + (a \sin^3 \theta)^{\frac{2}{3}} \\ &= a^{\frac{2}{3}} (\cos^2 \theta + \sin^2 \theta) = a^{\frac{2}{3}} \end{aligned}$$

hence, $x = a \cos^3 \theta$, $y = a \sin^3 \theta$ is parametric equation of $x^{\frac{2}{3}} + y^{\frac{2}{3}} = a^{\frac{2}{3}}$

now

$$\frac{dx}{d\theta} = -3a \cos^2 \theta \sin \theta \quad \text{and} \quad \frac{dy}{d\theta} = 3a \sin^2 \theta \cos \theta$$

denoted by y'' or y_2 if $y=f(x)$. We remark that higher order derivatives may be defined similarly.

Example 38 Find $\frac{d^2y}{dx^2}$, if $y = x \tan x$.

Solution Given that $y = x \tan x$. Then

$$\frac{dy}{dx} = x^2 \sec^2 x$$

Therefore

$$\begin{aligned} \frac{d^2y}{dx^2} &= \frac{d}{dx} (x^2 \sec^2 x) \\ &= x \cdot 2 \sec x \cdot \sec x \tan x + x^2 \sec^2 x \tan x \end{aligned}$$

Example 39 If $y = A \sin x \cos x$, then prove that $\frac{d^2y}{dx^2} + y = 0$.

Solution We have

$$\frac{dy}{dx} = A \cos x - \sin x$$

and

$$\begin{aligned} \frac{d^2y}{dx^2} &= \frac{d}{dx} (A \cos x - \sin x) \\ &= -A \sin x - \cos x = -y \end{aligned}$$

ence

$$\frac{d^2y}{dx^2} + y = 0$$

Example 40 If $y = e^{2x} - 2e^x$, prove that $\frac{d^2y}{dx^2} - 5\frac{dy}{dx} + 0y = 0$.

Solution Given that $y = e^{2x} - 2e^x$. Then

$$\frac{dy}{dx} = 2e^{2x} - 2e^x = 2(e^{2x} - e^x)$$

Therefore

$$\frac{d^2y}{dx^2} = 4e^{2x} - 2e^x = 2(e^{2x} - e^x)$$

ence

$$\begin{aligned} \frac{d^2y}{dx^2} - 5\frac{dy}{dx} + 0y &= 2(e^{2x} - e^x) - 5 \cdot 2(e^{2x} - e^x) \\ &= 0(e^{2x} - e^x) = 0 \end{aligned}$$

Example 41 If $y = \sin^{-1} x$, show that $(1 - x^2) \frac{d^2 y}{dx^2} - x \frac{dy}{dx} = 0$.

Solution We have $y = \sin^{-1} x$. Then

$$\frac{dy}{dx} = \frac{1}{\sqrt{1-x^2}}$$

or
$$\sqrt{1-x^2} \frac{dy}{dx} = 1$$

o
$$\frac{d}{dx} \left(\sqrt{1-x^2} \cdot \frac{dy}{dx} \right) = 0$$

or
$$\sqrt{1-x^2} \cdot \frac{d^2 y}{dx^2} + \frac{dy}{dx} \cdot \frac{d}{dx} \left(\sqrt{1-x^2} \right) = 0$$

or
$$\sqrt{1-x^2} \cdot \frac{d^2 y}{dx^2} - \frac{dy}{dx} \cdot \frac{2x}{2\sqrt{1-x^2}} = 0$$

ence
$$(1-x^2) \frac{d^2 y}{dx^2} - x \frac{dy}{dx} = 0$$

Alternatively, Given that $y = \sin^{-1} x$, we have

$$y_1 = \frac{1}{\sqrt{1-x^2}}, \text{ i.e., } (1-x^2)y_1^2 = 1$$

o
$$(1-x^2) \cdot 2y_1 y_2 + y_1^2 (0-2x) = 0$$

ence
$$(1-x^2)y_2 - xy_1 = 0$$

EXERCISE 5.7

Find the second order derivatives of the functions given in exercises 1 to 10.

- 1. $x^2 - x^2$ 2. x^{20} 3. $x \cdot \cos x$
- 4. $\log x$ 5. $x \log x$ 6. $e^x \sin 5x$
- 7. $e^x \cos x$ 8. $\tan^{-1} x$ 9. $\log(\log x)$
- 10. $\sin(\log x)$
- 11. If $y = 5 \cos x - \sin x$, prove that $\frac{d^2 y}{dx^2} + y = 0$

- 12. If $y = \cos^{-1} x$, Find $\frac{d^2y}{dx^2}$ in terms of y alone.
- 13. If $y = \cos(\log x) \sin(\log x)$, show that $x^2 y_2 - xy_1 - y = 0$
- 14. If $y = Ae^{mx} + Be^{-mx}$, show that $\frac{d^2y}{dx^2} - (m+n)\frac{dy}{dx} + mny = 0$
- 15. If $y = 500e^x + 100e^{-x}$, show that $\frac{d^2y}{dx^2} = y$
- 16. If $e^y(x-1) = 1$, show that $\frac{d^2y}{dx^2} = \left(\frac{dy}{dx}\right)^2$
- 17. If $y = (\tan^{-1} x)^2$, show that $(x^2 + 1)^{-2} y_2 - 2x(x^2 + 1)^{-3} y_1 = 2$

5.8 Mean Value Theorem

In this section, we will state two fundamental results in Calculus without proof. We shall also learn the geometric interpretation of these theorems.

Theorem 6 (Rolle's Theorem) Let $f : [a, b] \rightarrow \mathbf{R}$ be continuous on $[a, b]$ and differentiable on (a, b) , such that $f(a) = f(b)$, where a and b are some real numbers. Then there exists some c in (a, b) such that $f'(c) = 0$.

In Fig 5.12 and 5.1, graphs of a few typical differentiable functions satisfying the hypothesis of Rolle's theorem are given.

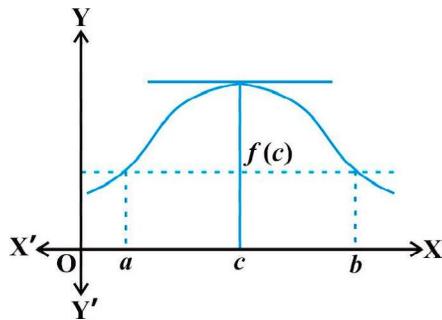


Fig 5.12

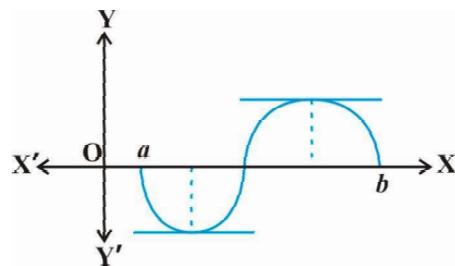


Fig 5.13

Observe what happens to the slope of the tangent to the curve at various points between a and b . In each of the graphs, the slope becomes zero at least at one point. That is precisely the claim of the Rolle's theorem as the slope of the tangent at any point on the graph of $y = f(x)$ is nothing but the derivative of $f(x)$ at that point.

Theorem 7 (Mean value Theorem) Let $f : [a, b] \rightarrow \mathbf{R}$ be a continuous function on $[a, b]$ and differentiable on (a, b) . Then there exists some c in (a, b) such that

$$f'(c) = \frac{f(b) - f(a)}{b - a}$$

Observe that the Mean value Theorem (MT) is an extension of Rolle's theorem. Let us now understand a geometric interpretation of the MT. The graph of a function $y = f(x)$ is given in the Fig 5.1. We have already interpreted $f'(c)$ as the slope of the tangent to the curve $y = f(x)$ at $(c, f(c))$. From the Fig 5.1 it is clear that $\frac{f(b) - f(a)}{b - a}$ is the slope of the secant drawn between $(a, f(a))$ and $(b, f(b))$. The MT states that there is a point c in (a, b) such that the slope of the tangent at $(c, f(c))$ is same as the slope of the secant between $(a, f(a))$ and $(b, f(b))$. In other words, there is a point c in (a, b) such that the tangent at $(c, f(c))$ is parallel to the secant between $(a, f(a))$ and $(b, f(b))$.

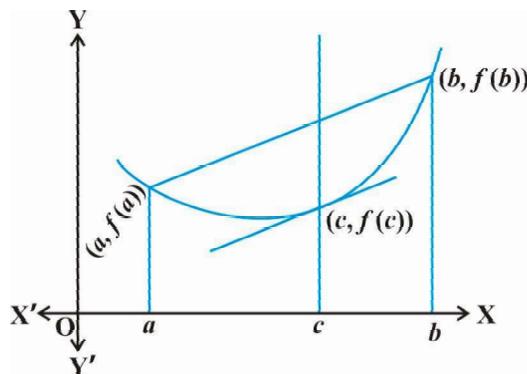


Fig 5.14

Example 42 Verify Rolle's theorem for the function $y = x^2 - 2$, $a = -2$ and $b = 2$.

Solution The function $y = x^2 - 2$ is continuous in $[-2, 2]$ and differentiable in $(-2, 2)$. Also $f(-2) = f(2) = -2$ and hence the value of $f(x)$ at -2 and 2 coincide. Rolle's theorem states that there is a point $c \in (-2, 2)$, where $f'(c) = 0$. Since $f'(x) = 2x$, we get $c = 0$. Thus at $c = 0$, we have $f'(c) = 0$ and $c = 0 \in (-2, 2)$.

Example 43 Verify Mean value Theorem for the function $f(x) = x^2$ in the interval $[2, 4]$.

Solution The function $f(x) = x^2$ is continuous in $[2, 4]$ and differentiable in $(2, 4)$ as its derivative $f'(x) = 2x$ is defined in $(2, 4)$.

ow, $f(2) =$ and $f() = 1$. ence

$$\frac{f(b) - f(a)}{b - a} = \frac{1 -}{2 -} =$$

MT states that there is a point $c \in (2,)$ such that $f'(c) =$. ut $f'(x) = 2x$ which implies $c =$. Thus at $c = \in (2,)$, we have $f'(c) =$.

EXERCISE 5.8

1. erify olle s theorem for the function $f(x) = x^2 - 2x -$, $x \in -$, 2.
2. xamine if olle s theorem is applicable to any of the following functions. Can you say some thing about the converse of olle s theorem from these example
 - (i) $f(x) = x$ for $x \in 5$, (ii) $f(x) = x$ for $x \in -2, 2$
 - (iii) $f(x) = x^2 - 1$ for $x \in 1, 2$
3. If $f : -5, 5 \rightarrow \mathbf{R}$ is a differentiable function and if $f'(x)$ does not vanish anywhere, then prove that $f(-5) \neq f(5)$.
4. erify Mean alue Theorem, if $f(x) = x^2 - x -$ in the interval a, b , where $a = 1$ and $b =$.
5. erify Mean alue Theorem, if $f(x) = x - 5x^2 - x$ in the interval a, b , where $a = 1$ and $b =$. Find all $c \in (1,)$ for which $f'(c) = 0$.
6. xamine the applicability of Mean alue Theorem for all three functions given in the above exercise 2.

Miscellaneous Examples

Example 44 iff erentiate w.r.t. x , the following function

(i) $\sqrt{2x+} + \frac{1}{\sqrt{2x^2+}}$ (ii) $e^{\sec^2 x} + \cos^{-1} x$ (iii) $\log(\log x)$

Solution

(i) et $y = \sqrt{2x+} + \frac{1}{\sqrt{2x^2+}} = (2x+)^{\frac{1}{2}} + (2+)^{-\frac{1}{2}} x^2 +$

ote that this function is defined at all real numbers $x > -\frac{2}{}$. Therefore

$$\frac{dy}{dx} = \frac{1}{2}(2x+)^{-\frac{1}{2}} + \frac{1}{2} (2+)^{-\frac{1}{2}-1} x^2 + (2+)^{-\frac{1}{2}} \left(-\frac{1}{2}\right) x^2 + (2+)^{-\frac{1}{2}-1} \frac{d}{dx} x^2 +$$

$$\begin{aligned}
 &= \frac{1}{2} (2x + 1)^{-\frac{1}{2}} \cdot \left(2 \cdot \frac{1}{2}\right) x^2 + \dots \cdot x \\
 &= \frac{2}{2\sqrt{2x+1}} - \frac{x}{(2x^2 + 1)^{\frac{3}{2}}}
 \end{aligned}$$

This is defined for all real numbers $x > -\frac{1}{2}$.

(ii) et $y = e^{\sec^2 x} + \cos^{-1} x$

This is defined at every real number in $]-1, 1[$. Therefore

$$\begin{aligned}
 \frac{dy}{dx} &= e^{\sec^2 x} \cdot \frac{d}{dx} (\sec^2 x) + \left(-\frac{1}{\sqrt{1-x^2}} \right) \\
 &= e^{\sec^2 x} \cdot \left(2 \sec x \frac{d}{dx} (\sec x) \right) + \left(-\frac{1}{\sqrt{1-x^2}} \right) \\
 &= 2 \sec x (\sec x \tan x) e^{\sec^2 x} + \left(-\frac{1}{\sqrt{1-x^2}} \right) \\
 &= 2 \sec^2 x \tan x e^{\sec^2 x} + \left(-\frac{1}{\sqrt{1-x^2}} \right)
 \end{aligned}$$

Observe that the derivative of the given function is valid only in $]-1, 1[\setminus \{0\}$ as the derivative of $\cos^{-1} x$ exists only in $(-1, 1)$ and the function itself is not defined at 0.

(iii) et $y = \log (\log x) = \frac{\log (\log x)}{\log 10}$ (by change of base formula).

The function is defined for all real numbers $x > 1$. Therefore

$$\begin{aligned}
 \frac{dy}{dx} &= \frac{1}{\log 10} \frac{d}{dx} (\log (\log x)) \\
 &= \frac{1}{\log 10} \frac{1}{x} \cdot \frac{d}{dx} (\log x) \\
 &= \frac{1}{x \log 10}
 \end{aligned}$$

Example 45 differentiate the following w.r.t. x .

$$(i) \cos^{-1}(\sin x) \quad (ii) \tan^{-1}\left(\frac{\sin x}{1 + \cos x}\right) \quad (iii) \sin^{-1}\left(\frac{2^{x+1}}{1+x}\right)$$

Solution

- (i) et $f(x) = \cos^{-1}(\sin x)$. Observe that this function is defined for all real numbers. We may rewrite this function as

$$\begin{aligned} f(x) &= \cos^{-1}(\sin x) \\ &= \cos^{-1}\left[\cos\left(\frac{\pi}{2} - x\right)\right] \\ &= \frac{\pi}{2} - x \end{aligned}$$

Thus $f'(x) = -1$.

- (ii) et $f(x) = \tan^{-1}\left(\frac{\sin x}{1 + \cos x}\right)$. Observe that this function is defined for all real numbers, where $\cos x \neq -1$ i.e., at all odd multiples of π . We may rewrite this function as

$$\begin{aligned} f(x) &= \tan^{-1}\left(\frac{\sin x}{1 + \cos x}\right) \\ &= \tan^{-1}\left[\frac{2 \sin\left(\frac{x}{2}\right) \cos\left(\frac{x}{2}\right)}{2 \cos^2 \frac{x}{2}}\right] \\ &= \tan^{-1}\left[\tan\left(\frac{x}{2}\right)\right] = \frac{x}{2} \end{aligned}$$

Observe that we could cancel $\cos\left(\frac{x}{2}\right)$ in both numerator and denominator as it is not equal to zero. Thus $f'(x) = \frac{1}{2}$.

- (iii) et $f(x) = \sin^{-1}\left(\frac{2^{x+1}}{1+x}\right)$. To find the domain of this function we need to find all

x such that $-1 \leq \frac{2^{x+1}}{1+x} \leq 1$. Since the quantity in the middle is always positive,

we need to find all x such that $\frac{2^{x+1}}{1+2^x} \leq 1$, i.e., all x such that $2^{x+1} \leq 1+2^x$. We

may rewrite this as $2 \leq \frac{1}{2^x} + 2^x$ which is true for all x . since the function is defined at every real number. y putting $2^{-x} = \tan \theta$, this function may be rewritten as

$$\begin{aligned} f(x) &= \sin^{-1} \left[\frac{2^{x+1}}{1+2^x} \right] \\ &= \sin^{-1} \left[\frac{2^x \cdot 2}{1+(2^x)^2} \right] \\ &= \sin^{-1} \left[\frac{2 \tan \theta}{1+\tan^2 \theta} \right] \\ &= \sin^{-1} \sin 2\theta \\ &= 2\theta = 2 \tan^{-1} (2^x) \end{aligned}$$

Thus

$$\begin{aligned} f'(x) &= 2 \cdot \frac{1}{1+(2^x)^2} \cdot \frac{d}{dx} (2^x) \\ &= \frac{2}{1+2^{2x}} \cdot (2^x) \log 2 \\ &= \frac{2^{x+1} \log 2}{1+2^{2x}} \end{aligned}$$

Example 46 Find $f'(x)$ if $f(x) = (\sin x)^{\sin x}$ for all $0 < x < \pi$.

Solution The function $y = (\sin x)^{\sin x}$ is defined for all positive real numbers. Taking logarithms, we have

$$\log y = \log (\sin x)^{\sin x} = \sin x \log (\sin x)$$

Then

$$\begin{aligned} \frac{1}{y} \frac{dy}{dx} &= \frac{d}{dx} (\sin x \log (\sin x)) \\ &= \cos x \log (\sin x) + \sin x \cdot \frac{1}{\sin x} \cdot \frac{d}{dx} (\sin x) \\ &= \cos x \log (\sin x) + \cos x \\ &= (1 + \log (\sin x)) \cos x \end{aligned}$$

Thus $\frac{dy}{dx} = y((1 - \log(\sin x)) \cos x) = (1 - \log(\sin x)) (\sin x)^{\sin x} \cos x$

Example 47 For a positive constant a find $\frac{dy}{dx}$, where

$$y = a^{t+\frac{1}{t}}, \text{ and } x = \left(t + \frac{1}{t}\right)^a$$

Solution Observe that both y and x are defined for all real $t \neq 0$. Clearly

$$\begin{aligned} \frac{dy}{dt} &= \frac{d}{dt} \left(a^{t+\frac{1}{t}} \right) = a^{t+\frac{1}{t}} \frac{d}{dt} \left(t + \frac{1}{t} \right) \cdot \log a \\ &= a^{t+\frac{1}{t}} \left(1 - \frac{1}{t^2} \right) \log a \end{aligned}$$

imilarly

$$\begin{aligned} \frac{dx}{dt} &= a \left[t + \frac{1}{t} \right]^{a-1} \cdot \frac{d}{dt} \left(t + \frac{1}{t} \right) \\ &= a \left[t + \frac{1}{t} \right]^{a-1} \cdot \left(1 - \frac{1}{t^2} \right) \end{aligned}$$

$\frac{dx}{dt} \neq 0$ only if $t \neq \pm 1$. Thus for $t \neq \pm 1$,

$$\begin{aligned} \frac{dy}{dx} &= \frac{\frac{dy}{dt}}{\frac{dx}{dt}} = \frac{a^{t+\frac{1}{t}} \left(1 - \frac{1}{t^2} \right) \log a}{a \left[t + \frac{1}{t} \right]^{a-1} \cdot \left(1 - \frac{1}{t^2} \right)} \\ &= \frac{a^{t+\frac{1}{t}} \log a}{a \left(t + \frac{1}{t} \right)^{a-1}} \end{aligned}$$

Example 48 Differentiate $\sin^2 x$ w.r.t. $e^{\cos x}$.

Solution Let $u(x) = \sin^2 x$ and $v(x) = e^{\cos x}$. We want to find $\frac{du}{dv} = \frac{du}{dx} \frac{dx}{dv}$. Clearly

$$\frac{du}{dx} = 2 \sin x \cos x \text{ and } \frac{dv}{dx} = e^{\cos x} (-\sin x) = -(\sin x) e^{\cos x}$$

Thus
$$\frac{du}{dv} = \frac{2 \sin x \cos x}{-\sin x e^{\cos x}} = -\frac{2 \cos x}{e^{\cos x}}$$

Miscellaneous Exercise on Chapter 5

ifferentiate w.r.t. x the function in exercises 1 to 11.

1. $(x^2 - x - 5)$
2. $\sin x \cos x$
3. $(5x)^{\cos x}$
4. $\sin^{-1}(x \sqrt{x}), 0 \leq x \leq 1$

5. $\frac{\cos^{-1} \frac{x}{2}}{\sqrt{2x+2}}, -2 < x < 2$

6. $\cot^{-1} \left[\frac{\sqrt{1+\sin x} + \sqrt{1-\sin x}}{\sqrt{1+\sin x} - \sqrt{1-\sin x}} \right], 0 < x < \frac{\pi}{2}$

7. $(\log x)^{\log x}, x > 1$

8. $\cos(a \cos x - b \sin x)$, for some constant a and b .

9. $(\sin x - \cos x)^{(\sin x - \cos x)}, \frac{\pi}{4} < x < \frac{3\pi}{4}$

10. $x^x - x^a - a^x - a^a$, for some fixed $a > 0$ and $x > 0$

11. $x^{x^2} + (x-1)^{x^2}$, for $x > 1$

12. Find $\frac{dy}{dx}$, if $y = 12(1 - \cos t)$, $x = 10(t - \sin t)$, $-\frac{\pi}{2} < t < \frac{\pi}{2}$

13. Find $\frac{dy}{dx}$, if $y = \sin^{-1} x \sin^{-1} \sqrt{1-x^2}$, $0 < x < 1$

14. If $x\sqrt{1+y} + y\sqrt{1+x} = 0$, for $-1 < x < 1$, prove that

$$\frac{dy}{dx} = -\frac{1}{(1+x)^2}$$

15. If $(x-a)^2 + (y-b)^2 = c^2$, for some $c > 0$, prove that

$$\frac{\left[1 + \left(\frac{dy}{dx} \right)^2 \right]^{\frac{3}{2}}}{\frac{d^2y}{dx^2}}$$

is a constant independent of a and b .

16. If $\cos y = x \cos (a - y)$, with $\cos a \neq 1$, prove that $\frac{dy}{dx} = \frac{\cos^2(a + y)}{\sin a}$.
17. If $x = a(\cos t - t \sin t)$ and $y = a(\sin t - t \cos t)$, find $\frac{d^2y}{dx^2}$.
18. If $f(x) = x^x$, show that $f''(x)$ exists for all real x and find it.
19. Using mathematical induction prove that $\frac{d}{dx}(x^n) = nx^{n-1}$ for all positive integers n .
20. Using the fact that $\sin(A \pm B) = \sin A \cos B \pm \cos A \sin B$ and the differentiation, obtain the sum formula for cosines.
21. Does there exist a function which is continuous everywhere but not differentiable at exactly two points? Justify your answer.
22. If $y = \begin{vmatrix} f(x) & g(x) & h(x) \\ l & m & n \\ a & b & c \end{vmatrix}$, prove that $\frac{dy}{dx} = \begin{vmatrix} f'(x) & g'(x) & h'(x) \\ l & m & n \\ a & b & c \end{vmatrix}$.
23. If $y = e^{a \cos^{-1} x}$, $-1 \leq x \leq 1$, show that $(1 - x^2) \frac{d^2y}{dx^2} - x \frac{dy}{dx} - a^2 y = 0$.

Summary

- ◆ A real valued function is **continuous** at a point in its domain if the limit of the function at that point equals the value of the function at that point. A function is continuous if it is continuous on the whole of its domain.
- ◆ Sum, difference, product and quotient of continuous functions are continuous. i.e., if f and g are continuous functions, then
 - $(f + g)(x) = f(x) + g(x)$ is continuous.
 - $(f - g)(x) = f(x) - g(x)$ is continuous.
 - $\left(\frac{f}{g}\right)(x) = \frac{f(x)}{g(x)}$ (wherever $g(x) \neq 0$) is continuous.
- ◆ Every differentiable function is continuous, but the converse is not true.

- ◆ Chain rule is rule to differentiate composites of functions. If $f = v \circ u$, $t = u(x)$

and if both $\frac{dt}{dx}$ and $\frac{dv}{dt}$ exist then

$$\frac{df}{dx} = \frac{dv}{dt} \cdot \frac{dt}{dx}$$

- ◆ Following are some of the standard derivatives (in appropriate domains)

$$\frac{d}{dx}(\sin^{-1} x) = \frac{1}{\sqrt{1-x^2}} \quad \frac{d}{dx}(\cos^{-1} x) = -\frac{1}{\sqrt{1-x^2}}$$

$$\frac{d}{dx}(\tan^{-1} x) = \frac{1}{1+x^2} \quad \frac{d}{dx}(\cot^{-1} x) = \frac{-1}{1+x^2}$$

$$\frac{d}{dx}(\sec^{-1} x) = \frac{1}{x\sqrt{1-x^2}} \quad \frac{d}{dx}(\operatorname{cosec}^{-1} x) = \frac{-1}{x\sqrt{1-x^2}}$$

$$\frac{d}{dx}(e^x) = e^x \quad \frac{d}{dx}(\log x) = \frac{1}{x}$$

- ◆ logarithmic differentiation is a powerful technique to differentiate functions of the form $f(x) = u(x)^{v(x)}$. Here both $f(x)$ and $u(x)$ need to be positive for this technique to make sense.
- ◆ **Rolle's Theorem** If $f: a, b \rightarrow \mathbf{R}$ is continuous on a, b and differentiable on (a, b) such that $f(a) = f(b)$, then there exists some c in (a, b) such that $f'(c) = 0$.
- ◆ **Mean Value Theorem** If $f: a, b \rightarrow \mathbf{R}$ is continuous on a, b and differentiable on (a, b) . Then there exists some c in (a, b) such that

$$f'(c) = \frac{f(b) - f(a)}{b - a}$$



APPLICATION OF DERIVATIVES

❖ *With the Calculus as a key, Mathematics can be successfully applied to the explanation of the course of Nature.* — WHITEHEAD ❖

6.1 Introduction

In Chapter 5, we have learnt how to find derivative of composite functions, inverse trigonometric functions, implicit functions, exponential functions and logarithmic functions. In this chapter, we will study applications of the derivative in various disciplines, e.g., in engineering, science, social science, and many other fields. For instance, we will learn how the derivative can be used (i) to determine rate of change of quantities, (ii) to find the equations of tangent and normal to a curve at a point, (iii) to find turning points on the graph of a function which in turn will help us to locate points at which largest or smallest value (locally) of a function occurs. We will also use derivative to find intervals on which a function is increasing or decreasing. Finally, we use the derivative to find approximate value of certain quantities.

6.2 Rate of Change of Quantities

Recall that by the derivative $\frac{ds}{dt}$, we mean the rate of change of distance s with respect to the time t . In a similar fashion, whenever one quantity y varies with another quantity x , satisfying some rule $y = f(x)$, then $\frac{dy}{dx}$ (or $f'(x)$) represents the rate of change of y with respect to x and $\left. \frac{dy}{dx} \right|_{x=x_0}$ (or $f'(x_0)$) represents the rate of change of y with respect to x at $x = x_0$.

Further, if two variables x and y are varying with respect to another variable t , i.e., if $x = f(t)$ and $y = g(t)$, then by Chain Rule

$$\frac{dy}{dx} = \frac{dy}{dt} \bigg/ \frac{dx}{dt}, \text{ if } \frac{dx}{dt} \neq 0$$

Thus, the rate of change of y with respect to x can be calculated using the rate of change of y and that of x both with respect to t .

Let us consider some examples.

Example 1 Find the rate of change of the area of a circle per second with respect to its radius r when $r = 5$ cm.

Solution The area A of a circle with radius r is given by $A = \pi r^2$. Therefore, the rate of change of the area A with respect to its radius r is given by $\frac{dA}{dr} = \frac{d}{dr}(\pi r^2) = 2\pi r$.

When $r = 5$ cm, $\frac{dA}{dr} = 10\pi$. Thus, the area of the circle is changing at the rate of 10π cm²/s.

Example 2 The volume of a cube is increasing at a rate of 9 cubic centimetres per second. How fast is the surface area increasing when the length of an edge is 10 centimetres?

Solution Let x be the length of a side, V be the volume and S be the surface area of the cube. Then, $V = x^3$ and $S = 6x^2$, where x is a function of time t .

Now
$$\frac{dV}{dt} = 9 \text{ cm}^3/\text{s} \quad (\text{given})$$

Therefore
$$\begin{aligned} 9 &= \frac{dV}{dt} = \frac{d}{dt}(x^3) = \frac{d}{dx}(x^3) \cdot \frac{dx}{dt} \quad (\text{by Chain Rule}) \\ &= 3x^2 \cdot \frac{dx}{dt} \end{aligned}$$

or
$$\frac{dx}{dt} = \frac{3}{x^2} \quad \dots (1)$$

Now
$$\begin{aligned} \frac{dS}{dt} &= \frac{d}{dt}(6x^2) = \frac{d}{dx}(6x^2) \cdot \frac{dx}{dt} \quad (\text{by Chain Rule}) \\ &= 12x \cdot \left(\frac{3}{x^2}\right) = \frac{36}{x} \quad (\text{using (1)}) \end{aligned}$$

Hence, when $x = 10$ cm, $\frac{dS}{dt} = 3.6 \text{ cm}^2/\text{s}$

Example 3 A stone is dropped into a quiet lake and waves move in circles at a speed of 4 cm per second. At the instant, when the radius of the circular wave is 10 cm, how fast is the enclosed area increasing?

Solution The area A of a circle with radius r is given by $A = \pi r^2$. Therefore, the rate of change of area A with respect to time t is

$$\frac{dA}{dt} = \frac{d}{dt}(\pi r^2) = \frac{d}{dr}(\pi r^2) \cdot \frac{dr}{dt} = 2\pi r \frac{dr}{dt} \quad (\text{by Chain Rule})$$

It is given that $\frac{dr}{dt} = 4 \text{ cm/s}$

Therefore, when $r = 10 \text{ cm}$, $\frac{dA}{dt} = 2\pi(10)(4) = 80\pi$

Thus, the enclosed area is increasing at the rate of $80\pi \text{ cm}^2/\text{s}$, when $r = 10 \text{ cm}$.

 **Note** $\frac{dy}{dx}$ is positive if y increases as x increases and is negative if y decreases as x increases.

Example 4 The length x of a rectangle is decreasing at the rate of 2 cm/minute and the width y is increasing at the rate of 3 cm/minute . When $x = 10 \text{ cm}$ and $y = 8 \text{ cm}$, find the rates of change of (a) the perimeter and (b) the area of the rectangle.

Solution Since the length x is decreasing and the width y is increasing with respect to time, we have

$$\frac{dx}{dt} = -2 \text{ cm/min} \quad \text{and} \quad \frac{dy}{dt} = 3 \text{ cm/min}$$

(a) The perimeter P of a rectangle is given by

$$P = 2(x + y)$$

Therefore $\frac{dP}{dt} = 2\left(\frac{dx}{dt} + \frac{dy}{dt}\right) = 2(-2 + 3) = 2 \text{ cm/min}$

(b) The area A of the rectangle is given by

$$A = x \cdot y$$

Therefore $\frac{dA}{dt} = \frac{dx}{dt} \cdot y + x \cdot \frac{dy}{dt}$
 $= (-2)(8) + 10(3) \quad (\text{as } x = 10 \text{ cm and } y = 8 \text{ cm})$
 $= 2 \text{ cm}^2/\text{min}$

Example 5 The total cost $C(x)$ in Rupees, associated with the production of x units of an item is given by

$$C(x) = 0.005x^3 - 0.04x^2 + 0.1x + 5000$$

Find the marginal cost when 10 units are produced, where by marginal cost we mean the instantaneous rate of change of total cost at any level of output.

Solution Since marginal cost is the rate of change of total cost with respect to the output, we have

Marginal cost (MC) = $\frac{dC}{dx} = 0.015x^2 - 0.08x + 0.1$

When $x = 10$, $MC = 0.15(10^2) - 0.08(10) + 0.1$
 $= 0.15 \times 100 - 0.8 + 0.1 = 14.3$

Hence, the required marginal cost is Rs 14.3 (nearly).

Example 6 The total revenue in Rupees received from the sale of x units of a product is given by $R(x) = 13x^2 - 5x + 5$. Find the marginal revenue, when $x = 5$, where by marginal revenue we mean the rate of change of total revenue with respect to the number of items sold at an instant.

Solution Since marginal revenue is the rate of change of total revenue with respect to the number of units sold, we have

Marginal Revenue (MR) = $\frac{dR}{dx} = 26x - 5$

When $x = 5$, $MR = 26(5) - 5 = 125$

Hence, the required marginal revenue is Rs 125

EXERCISE 6.1

1. Find the rate of change of the area of a circle with respect to its radius r when
 - (a) $r = 10$ cm
 - (b) $r = 4$ cm
2. The volume of a cube is increasing at the rate of $3 \text{ cm}^3/\text{s}$. How fast is the surface area increasing when the length of an edge is 10 cm?
3. The radius of a circle is increasing uniformly at the rate of 3 cm/s . Find the rate at which the area of the circle is increasing when the radius is 10 cm.
4. An edge of a variable cube is increasing at the rate of 3 cm/s . How fast is the volume of the cube increasing when the edge is 10 cm long?
5. A stone is dropped into a quiet lake and waves move in circles at the speed of 5 cm/s . At the instant when the radius of the circular wave is 10 cm, how fast is the enclosed area increasing?

6. The radius of a circle is increasing at the rate of 0.5 cm/s . What is the rate of increase of its circumference?
7. The length x of a rectangle is decreasing at the rate of 5 cm/minute and the width y is increasing at the rate of 4 cm/minute . When $x = 8 \text{ cm}$ and $y = 6 \text{ cm}$, find the rates of change of (a) the perimeter, and (b) the area of the rectangle.
8. A balloon, which always remains spherical on inflation, is being inflated by pumping in 900 cubic centimetres of gas per second. Find the rate at which the radius of the balloon increases when the radius is 15 cm .
9. A balloon, which always remains spherical has a variable radius. Find the rate at which its volume is increasing with the radius when the latter is 10 cm .
10. A ladder 5 m long is leaning against a wall. The bottom of the ladder is pulled along the ground, away from the wall, at the rate of 2 cm/s . How fast is its height on the wall decreasing when the foot of the ladder is 4 m away from the wall?
11. A particle moves along the curve $y = x^2$. Find the points on the curve at which the y -coordinate is changing n times as fast as the x -coordinate.
12. The radius of an air bubble is increasing at the rate of $\frac{1}{4} \text{ cm/s}$. At what rate is the volume of the bubble increasing when the radius is 1 cm ?
13. A balloon, which always remains spherical, has a variable diameter $\frac{1}{4}(x+1)$. Find the rate of change of its volume with respect to x .
14. Sand is pouring from a pipe at the rate of $1 \text{ cm}^3/\text{s}$. The falling sand forms a cone on the ground in such a way that the height of the cone is always one-sixth of the radius of the base. How fast is the height of the sand cone increasing when the height is 4 cm ?
15. The total cost $C(x)$ in Rupees associated with the production of x units of an item is given by
- $$C(x) = 0.00x^3 + 0.00x^2 + 15x + 4000.$$
- Find the marginal cost when 1 unit is produced.
16. The total revenue in Rupees received from the sale of x units of a product is given by
- $$R(x) = 10x^2 + 15x.$$
- Find the marginal revenue when $x = 10$.
- Choose the correct answer in the Exercises 10 and 11.
17. The rate of change of the area of a circle with respect to its radius r at $r = 3 \text{ cm}$ is
 (A) 10π (B) 12π (C) 9π (D) 11π

18. The total revenue in Rupees received from the sale of x units of a product is given by

$$R(x) = x^2 - 2x + 5. \text{ The marginal revenue, when } x = 15 \text{ is}$$

- (A) 11 (B) 9 (C) 90 (D) 100

6.3 Increasing and Decreasing Functions

In this section, we will use differentiation to find out whether a function is increasing or decreasing or none.

Consider the function f given by $f(x) = x^2, x \in \mathbf{R}$. The graph of this function is a parabola as given in Fig 6.1.

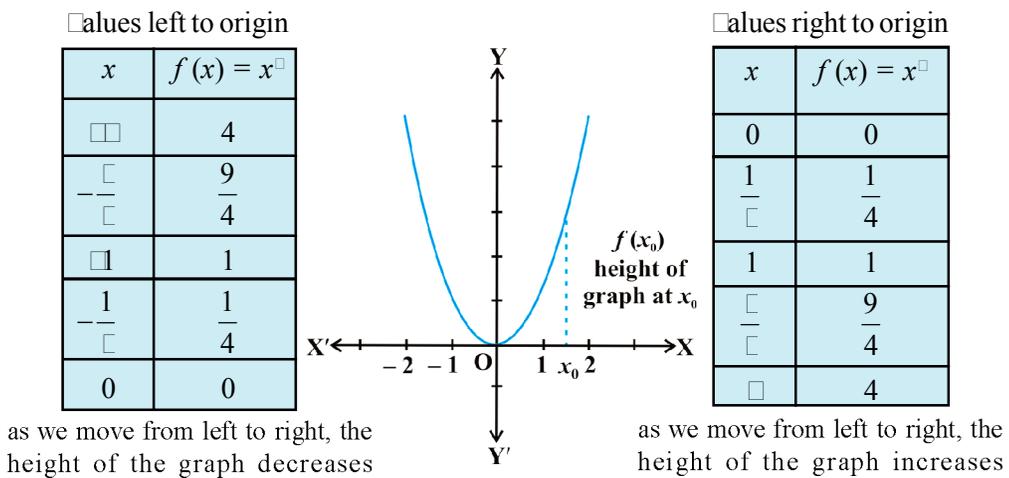


Fig 6.1

First consider the graph (Fig 6.1) to the right of the origin. Observe that as we move from left to right along the graph, the height of the graph continuously increases. For this reason, the function is said to be increasing for the real numbers $x \geq 0$.

Now consider the graph to the left of the origin and observe here that as we move from left to right along the graph, the height of the graph continuously decreases. Consequently, the function is said to be decreasing for the real numbers $x \leq 0$.

We shall now give the following analytical definitions for a function which is increasing or decreasing on an interval.

Definition 1 Let I be an interval contained in the domain of a real valued function f . Then f is said to be

- (i) increasing on I if $x_1 < x_2$ in $I \Rightarrow f(x_1) \leq f(x_2)$ for all $x_1, x_2 \in I$.
- (ii) strictly increasing on I if $x_1 < x_2$ in $I \Rightarrow f(x_1) < f(x_2)$ for all $x_1, x_2 \in I$.

- (iii) decreasing on I if $x_1 < x_2$ in I $\Rightarrow f(x_1) \geq f(x_2)$ for all $x_1, x_2 \in I$.
- (iv) strictly decreasing on I if $x_1 < x_2$ in I $\Rightarrow f(x_1) > f(x_2)$ for all $x_1, x_2 \in I$.

For graphical representation of such functions see Fig 6.2

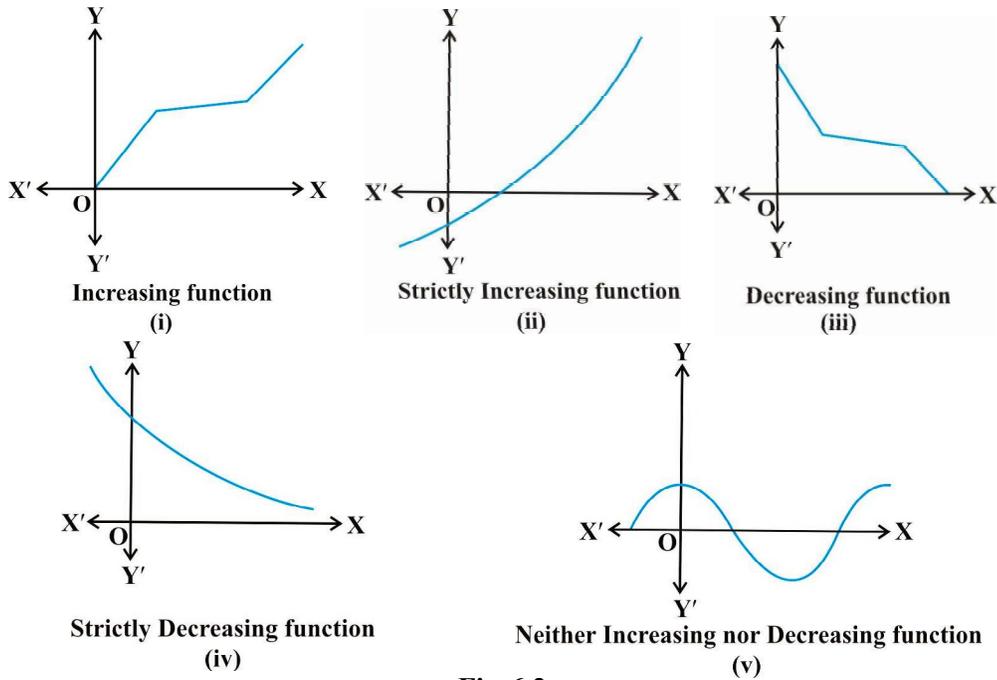


Fig 6.2

We shall now define when a function is increasing or decreasing at a point.

Definition 2 Let x_0 be a point in the domain of definition of a real valued function f . Then f is said to be increasing, strictly increasing, decreasing or strictly decreasing at x_0 if there exists an open interval I containing x_0 such that f is increasing, strictly increasing, decreasing or strictly decreasing, respectively, in I.

Let us clarify this definition for the case of increasing function.

A function f is said to be increasing at x_0 if there exists an interval $I = (x_0 - h, x_0 + h)$, $h > 0$ such that for $x_1, x_2 \in I$

$$x_1 < x_2 \text{ in } I \Rightarrow f(x_1) \leq f(x_2)$$

Similarly, the other cases can be clarified.

Example 7 Show that the function given by $f(x) = x^2$ is strictly increasing on \mathbf{R} .

Solution Let x_1 and x_2 be any two numbers in \mathbf{R} . Then

$$x_1 < x_2 \Rightarrow x_1^2 < x_2^2 \Rightarrow f(x_1) < f(x_2)$$

Thus, by Definition 1, it follows that f is strictly increasing on \mathbf{R} .

We shall now give the first derivative test for increasing and decreasing functions. The proof of this test requires the Mean Value Theorem studied in Chapter 5.

Theorem 1 Let f be continuous on $[a, b]$ and differentiable on the open interval (a, b) . Then

- (a) f is strictly increasing in $[a, b]$ if $f'(x) > 0$ for each $x \in (a, b)$
- (b) f is strictly decreasing in $[a, b]$ if $f'(x) < 0$ for each $x \in (a, b)$
- (c) f is a constant function in $[a, b]$ if $f'(x) = 0$ for each $x \in (a, b)$

Proof (a) Let $x_1, x_2 \in [a, b]$ be such that $x_1 < x_2$.

Then, by Mean Value Theorem (Theorem 5 in Chapter 5), there exists a point c between x_1 and x_2 such that

$$f(x_2) - f(x_1) = f'(c) (x_2 - x_1)$$

i.e. $f(x_2) - f(x_1) > 0$ (as $f'(c) > 0$ (given))

i.e. $f(x_2) > f(x_1)$

Thus, we have

$$x_1 < x_2 \Rightarrow f(x_1) < f(x_2), \text{ for all } x_1, x_2 \in [a, b]$$

Hence, f is an increasing function in $[a, b]$

The proofs of part (b) and (c) are similar. It is left as an exercise to the reader.

Remarks

- (i) There is a more generalised theorem, which states that if $f'(x) > 0$ for x in an interval excluding the end points and f is continuous in the interval, then f is strictly increasing. Similarly, if $f'(x) < 0$ for x in an interval excluding the end points and f is continuous in the interval, then f is strictly decreasing.
- (ii) If a function is strictly increasing or strictly decreasing in an interval I , then it is necessarily increasing or decreasing in I . However, the converse need not be true.

Example 8 Show that the function f given by

$$f(x) = x^3 - 3x^2 + 4x, x \in \mathbf{R}$$

is strictly increasing on \mathbf{R} .

Solution Note that

$$f'(x) = 3x^2 - 6x + 4$$

$$= (x^2 - x + 1) - 1$$

$$= (x - 1)^2 - 1 \geq 0, \text{ in every interval of } \mathbf{R}$$

Therefore, the function f is strictly increasing on \mathbf{R} .

Example 9 Prove that the function given by $f(x) = \cos x$ is

- (a) strictly decreasing in $(0, \pi)$
- (b) strictly increasing in $(\pi, 2\pi)$, and
- (c) neither increasing nor decreasing in $(0, 2\pi)$.

Solution Note that $f'(x) = -\sin x$

- (a) Since for each $x \in (0, \pi)$, $\sin x > 0$, we have $f'(x) < 0$ and so f is strictly decreasing in $(0, \pi)$.
- (b) Since for each $x \in (\pi, 2\pi)$, $\sin x < 0$, we have $f'(x) > 0$ and so f is strictly increasing in $(\pi, 2\pi)$.
- (c) Clearly by (a) and (b) above, f is neither increasing nor decreasing in $(0, 2\pi)$.

Example 10 Find the intervals in which the function f given by $f(x) = x^2 - 4x + 4$ is

- (a) strictly increasing
- (b) strictly decreasing

Solution We have

$$f(x) = x^2 - 4x + 4$$

or
$$f'(x) = 2x - 4$$

Therefore, $f'(x) = 0$ gives $x = 2$.
 The point $x = 2$ divides the real line into two disjoint intervals namely, $(-\infty, 2)$ and $(2, \infty)$ (Fig 6.3). In the interval $(-\infty, 2)$, $f'(x) = 2x - 4 < 0$.

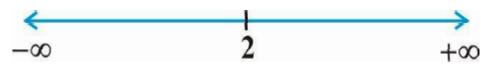


Fig 6.3

Therefore, f is strictly decreasing in this interval. Also, in the interval $(2, \infty)$, $f'(x) > 0$ and so the function f is strictly increasing in this interval.

Example 11 Find the intervals in which the function f given by $f(x) = 4x^3 - 3x^2 - 2x + 1$ is (a) strictly increasing (b) strictly decreasing.

Solution We have

$$f(x) = 4x^3 - 3x^2 - 2x + 1$$

or
$$\begin{aligned} f'(x) &= 1 \cdot x^2 - 1 \cdot x = x^2 - x \\ &= x(x - 1) \\ &= x(x - 1)(x + 1) \end{aligned}$$

Therefore, $f'(x) = 0$ gives $x = -1, 0, 1$. The points $x = -1$ and $x = 1$ divide the real line into three disjoint intervals, namely, $(-\infty, -1)$, $(-1, 1)$ and $(1, \infty)$.



Fig 6.4

In the intervals $(-\infty, -1)$ and $(1, \infty)$, $f'(x)$ is positive while in the interval $(-1, 1)$, $f'(x)$ is negative. Consequently, the function f is strictly increasing in the intervals $(-\infty, -1)$ and $(1, \infty)$ while the function is strictly decreasing in the interval $(-1, 1)$. However, f is neither increasing nor decreasing in \mathbf{R} .

Interval	Sign of $f'(x)$	Nature of function f
$(-\infty, -1)$	$(+)(+) > 0$	f is strictly increasing
$(-1, 1)$	$(+)(-) < 0$	f is strictly decreasing
$(1, \infty)$	$(-)(-) > 0$	f is strictly increasing

Example 12 Find intervals in which the function given by $f(x) = \sin x$, $x \in \left[0, \frac{\pi}{2}\right]$ is (a) increasing (b) decreasing.

Solution We have

or
$$\begin{aligned} f(x) &= \sin x \\ f'(x) &= \cos x \end{aligned}$$

Therefore, $f'(x) = 0$ gives $\cos x = 0$ which in turn gives $x = \frac{\pi}{2}$ (as $x \in \left[0, \frac{\pi}{2}\right]$) implies $x \in \left[0, \frac{\pi}{2}\right]$. So $x = \frac{\pi}{2}$. The point $x = \frac{\pi}{2}$ divides the interval $\left[0, \frac{\pi}{2}\right]$ into two disjoint intervals $\left[0, \frac{\pi}{2}\right)$ and $\left(\frac{\pi}{2}, \frac{\pi}{2}\right]$.

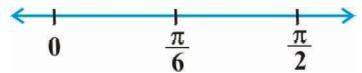


Fig 6.5

Now, $f'(x) > 0$ for all $x \in \left[0, \frac{\pi}{2}\right)$ as $0 \leq x < \frac{\pi}{2} \Rightarrow 0 \leq \cos x < \frac{\pi}{2}$ and $f'(x) < 0$ for all $x \in \left(\frac{\pi}{2}, \frac{\pi}{2}\right]$ as $\frac{\pi}{2} < x < \frac{\pi}{2} \Rightarrow \frac{\pi}{2} < \cos x < \frac{\pi}{2}$.

Therefore, f is strictly increasing in $\left[0, \frac{\pi}{4}\right)$ and strictly decreasing in $\left(\frac{\pi}{4}, \pi\right]$.

Also, the given function is continuous at $x=0$ and $x = \frac{\pi}{4}$. Therefore, by Theorem 1,

f is increasing on $\left[0, \frac{\pi}{4}\right]$ and decreasing on $\left[\frac{\pi}{4}, \pi\right]$.

Example 13 Find the intervals in which the function f given by

$$f(x) = \sin x - \cos x, \quad 0 \leq x \leq \pi$$

is strictly increasing or strictly decreasing.

Solution We have

$$f(x) = \sin x - \cos x,$$

or
$$f'(x) = \cos x + \sin x$$

Now $f'(x) = 0$ gives $\sin x = \cos x$ which gives that $x = \frac{\pi}{4}, \frac{5\pi}{4}$ as $0 \leq x \leq \pi$

The points $x = \frac{\pi}{4}$ and $x = \frac{5\pi}{4}$ divide the interval $[0, \pi]$ into three disjoint intervals,

namely, $\left[0, \frac{\pi}{4}\right)$, $\left(\frac{\pi}{4}, \frac{5\pi}{4}\right)$ and $\left(\frac{5\pi}{4}, \pi\right]$.

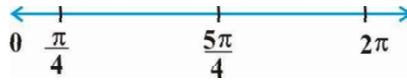


Fig 6.6

Note that $f'(x) > 0$ if $x \in \left[0, \frac{\pi}{4}\right) \cup \left(\frac{5\pi}{4}, \pi\right]$

or f is strictly increasing in the intervals $\left[0, \frac{\pi}{4}\right)$ and $\left(\frac{5\pi}{4}, \pi\right]$

Also $f'(x) < 0$ if $x \in \left(\frac{\pi}{4}, \frac{5\pi}{4}\right)$

or f is strictly decreasing in $\left(\frac{\pi}{4}, \frac{5\pi}{4}\right)$

Interval	Sign of $f'(x)$	Nature of function
$\left[0, \frac{\pi}{4}\right)$	> 0	f is strictly increasing
$\left(\frac{\pi}{4}, \frac{5\pi}{4}\right)$	< 0	f is strictly decreasing
$\left(\frac{5\pi}{4}, \pi\right]$	> 0	f is strictly increasing

EXERCISE 6.2

- Show that the function given by $f(x) = x + 1$ is strictly increasing on \mathbf{R} .
- Show that the function given by $f(x) = e^x$ is strictly increasing on \mathbf{R} .
- Show that the function given by $f(x) = \sin x$ is
 - strictly increasing in $\left(0, \frac{\pi}{2}\right)$
 - strictly decreasing in $\left(\frac{\pi}{2}, \pi\right)$
 - neither increasing nor decreasing in $(0, \pi)$
- Find the intervals in which the function f given by $f(x) = x^2 + x$ is
 - strictly increasing
 - strictly decreasing
- Find the intervals in which the function f given by $f(x) = x^2 + x^3 + x^4$ is
 - strictly increasing
 - strictly decreasing
- Find the intervals in which the following functions are strictly increasing or decreasing
 - $x^2 + x + 5$
 - $10 - x + x^2$
 - $x^2 + 9x^2 + 1 - x + 1$
 - $9x - x^2$
 - $(x + 1)^2 (x - 2)^2$
- Show that $y = \log(1 + x) - \frac{x}{1+x}$, $x \geq 0$, is an increasing function of x throughout its domain.
- Find the values of x for which $y = \ln(x + 1)$ is an increasing function.
- Prove that $y = \frac{4 \sin \theta}{(1 + \cos \theta)} - \theta$ is an increasing function of θ in $\left[0, \frac{\pi}{2}\right]$.

10. Prove that the logarithmic function is strictly increasing on $(0, \infty)$.
11. Prove that the function f given by $f(x) = x^x - x - 1$ is neither strictly increasing nor strictly decreasing on $(1, 1)$.
12. Which of the following functions are strictly decreasing on $\left(0, \frac{\pi}{2}\right)$?
 (A) $\cos x$ (B) $\cos^2 x$ (C) $\cos^3 x$ (D) $\tan x$
13. In which of the following intervals is the function f given by $f(x) = x^{100} - \sin x$ strictly decreasing ?
 (A) $(0, 1)$ (B) $\left(\frac{\pi}{2}, \pi\right)$ (C) $\left(0, \frac{\pi}{2}\right)$ (D) None of these
14. Find the least value of a such that the function f given by $f(x) = x^a - ax - 1$ is strictly increasing on $[1, \infty)$.
15. Let I be any interval disjoint from $[-1, 1]$. Prove that the function f given by $f(x) = x + \frac{1}{x}$ is strictly increasing on I .
16. Prove that the function f given by $f(x) = \log \sin x$ is strictly increasing on $\left(0, \frac{\pi}{2}\right)$ and strictly decreasing on $\left(\frac{\pi}{2}, \pi\right)$.
17. Prove that the function f given by $f(x) = \log |\cos x|$ is strictly decreasing on $\left(0, \frac{\pi}{2}\right)$ and strictly increasing on $\left(\frac{3\pi}{2}, \pi\right)$.
18. Prove that the function given by $f(x) = x^x - x^x - x^x - 100$ is increasing in \mathbf{R} .
19. The interval in which $y = x^x e^{-x}$ is increasing is
 (A) $(-\infty, \infty)$ (B) $(-\infty, 0)$ (C) $(0, \infty)$ (D) $(0, 1)$

6.4 Tangents and Normals

In this section, we shall use differentiation to find the equation of the tangent line and the normal line to a curve at a given point.

Recall that the equation of a straight line passing through a given point (x_0, y_0) having finite slope m is given by

$$y - y_0 = m(x - x_0)$$

Note that the slope of the tangent to the curve $y = f(x)$ at the point (x_0, y_0) is given by $\left. \frac{dy}{dx} \right|_{(x_0, y_0)} (= f'(x_0))$. So the equation of the tangent at (x_0, y_0) to the curve $y = f(x)$ is given by

$$y - y_0 = f'(x_0)(x - x_0)$$

Also, since the normal is perpendicular to the tangent, the slope of the normal to the curve $y = f(x)$ at (x_0, y_0) is

$-\frac{1}{f'(x_0)}$, if $f'(x_0) \neq 0$. Therefore, the equation of the

normal to the curve $y = f(x)$ at (x_0, y_0) is given by

$$y - y_0 = -\frac{1}{f'(x_0)}(x - x_0)$$

i.e. $(y - y_0)f'(x_0) + (x - x_0) = 0$

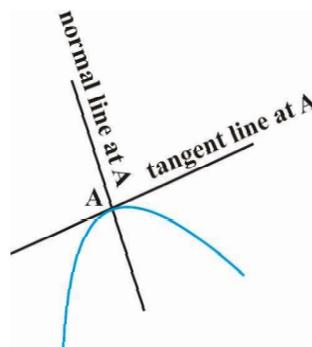


Fig 6.7

Note If a tangent line to the curve $y = f(x)$ makes an angle θ with x -axis in the positive direction, then $\left. \frac{dy}{dx} \right|_{(x_0, y_0)} = \text{slope of the tangent} = \tan \theta$.

Particular cases

- (i) If slope of the tangent line is zero, then $\tan \theta = 0$ and so $\theta = 0$ which means the tangent line is parallel to the x -axis. In this case, the equation of the tangent at the point (x_0, y_0) is given by $y = y_0$.
- (ii) If $\theta \rightarrow \frac{\pi}{2}$, then $\tan \theta \rightarrow \infty$, which means the tangent line is perpendicular to the x -axis, i.e., parallel to the y -axis. In this case, the equation of the tangent at (x_0, y_0) is given by $x = x_0$ (Why?).

Example 14 Find the slope of the tangent to the curve $y = x^2 - x$ at $x = 1$

Solution The slope of the tangent at $x = 1$ is given by

$$\left. \frac{dy}{dx} \right|_{x=1} = [2x - 1]_{x=1} = 1.$$

Example 15 Find the point at which the tangent to the curve $y = \sqrt{4x - 4} - 1$ has its slope $\frac{1}{2}$.

Solution Slope of tangent to the given curve at (x, y) is

$$\frac{dy}{dx} = \frac{1}{2}(4x - 4)^{-\frac{1}{2}} \cdot 4 = \frac{2}{\sqrt{4x - 4}}$$

The slope is given to be $\frac{1}{2}$.

So
$$\frac{2}{\sqrt{4x - 4}} = \frac{1}{2}$$

or
$$4x - 4 = 9$$

or
$$x = \frac{13}{4}$$

Now $y = \sqrt{4x - 4} - 1$. So when $x = \frac{13}{4}$, $y = \sqrt{4(\frac{13}{4}) - 4} - 1 = \frac{3}{2}$.

Therefore, the required point is $(\frac{13}{4}, \frac{3}{2})$.

Example 16 Find the equation of all lines having slope 1 and being tangent to the curve

$$y + \frac{1}{x - 4} = 0.$$

Solution Slope of the tangent to the given curve at any point (x, y) is given by

$$\frac{dy}{dx} = \frac{-1}{(x - 4)^2}$$

But the slope is given to be 1. Therefore

$$\frac{-1}{(x - 4)^2} = 1$$

or
$$(x - 4)^2 = -1$$

or
$$x - 4 = \pm 1$$

or
$$x = 3, 5$$

Now $x = 3$ gives $y = \frac{1}{3 - 4} = -1$ and $x = 5$ gives $y = \frac{1}{5 - 4} = 1$. Thus, there are two tangents to the given curve with slope 1 and passing through the points $(3, -1)$ and $(5, 1)$. The equation of tangent through $(3, -1)$ is given by

$$y - (-1) = 1(x - 3)$$

or
$$y + 1 = x - 3$$

and the equation of the tangent through $(5, 1)$ is given by

$$y - 1 = 1(x - 5)$$

or
$$y - 1 = x - 5$$

Example 17 Find points on the curve $\frac{x^2}{4} + \frac{y^2}{25} = 1$ at which the tangents are (i) parallel to x -axis (ii) parallel to y -axis.

Solution Differentiating $\frac{x^2}{4} + \frac{y^2}{25} = 1$ with respect to x , we get

$$\frac{x}{2} + \frac{2y}{25} \frac{dy}{dx} = 0$$

or

$$\frac{dy}{dx} = \frac{-25x}{4y}$$

(i) Now, the tangent is parallel to the x -axis if the slope of the tangent is zero which

gives $\frac{-25x}{4y} = 0$. This is possible if $x = 0$. Then $\frac{x^2}{4} + \frac{y^2}{25} = 1$ for $x = 0$ gives $y^2 = 25$, i.e., $y = \pm 5$.

Thus, the points at which the tangents are parallel to the x -axis are $(0, 5)$ and $(0, -5)$.

(ii) The tangent line is parallel to y -axis if the slope of the normal is 0 which gives

$\frac{4y}{25x} = 0$, i.e., $y = 0$. Therefore, $\frac{x^2}{4} + \frac{y^2}{25} = 1$ for $y = 0$ gives $x = \pm 2$. Hence, the points at which the tangents are parallel to the y -axis are $(2, 0)$ and $(-2, 0)$.

Example 18 Find the equation of the tangent to the curve $y = \frac{x-1}{(x-1)(x-4)}$ at the point where it cuts the x -axis.

Solution Note that on x -axis, $y = 0$. So the equation of the curve, when $y = 0$, gives $x = 1$. Thus, the curve cuts the x -axis at $(1, 0)$. Now differentiating the equation of the curve with respect to x , we obtain

$$\frac{dy}{dx} = \frac{1 - y(4x - 5)}{(x - 1)(x - 4)} \quad (\text{Why?})$$

or

$$\left. \frac{dy}{dx} \right|_{(1,0)} = \frac{1 - 0}{(5)(4)} = \frac{1}{20}$$

Therefore, the slope of the tangent at $(a, 0)$ is $\frac{1}{a}$. Hence, the equation of the tangent at $(a, 0)$ is

$$y - 0 = \frac{1}{a}(x - a) \quad \text{or} \quad ay - x + a = 0$$

Example 19 Find the equations of the tangent and normal to the curve $x^{\frac{1}{2}} + y^{\frac{1}{2}} = 1$ at $(1, 1)$.

Solution Differentiating $x^{\frac{1}{2}} + y^{\frac{1}{2}} = 1$ with respect to x , we get

$$\frac{1}{2}x^{-\frac{1}{2}} + \frac{1}{2}y^{-\frac{1}{2}} \frac{dy}{dx} = 0$$

or
$$\frac{dy}{dx} = -\left(\frac{y}{x}\right)^{\frac{1}{2}}$$

Therefore, the slope of the tangent at $(1, 1)$ is $\left.\frac{dy}{dx}\right|_{(1,1)} = -1$.

So the equation of the tangent at $(1, 1)$ is

$$y - 1 = -1(x - 1) \quad \text{or} \quad y - x + 1 = 0$$

Also, the slope of the normal at $(1, 1)$ is given by

$$\frac{-1}{\text{slope of the tangent at } (1,1)} = 1$$

Therefore, the equation of the normal at $(1, 1)$ is

$$y - 1 = 1(x - 1) \quad \text{or} \quad y - x = 0$$

Example 20 Find the equation of tangent to the curve given by

$$x = a \sin^2 t, \quad y = b \cos^2 t \quad \dots (1)$$

at a point where $t = \frac{\pi}{4}$.

Solution Differentiating (1) with respect to t , we get

$$\frac{dx}{dt} = 2a \sin t \cos t \quad \text{and} \quad \frac{dy}{dt} = -2b \cos t \sin t$$

or

$$\frac{dy}{dx} = \frac{\frac{dy}{dt}}{\frac{dx}{dt}} = \frac{-b \cos t \sin t}{a \sin^2 t \cos t} = \frac{-b \cos t}{a \sin t}$$

Therefore, slope of the tangent at $t = \frac{\pi}{2}$ is

$$\left. \frac{dy}{dx} \right|_{t=\frac{\pi}{2}} = \frac{-b \cos \frac{\pi}{2}}{a \sin \frac{\pi}{2}} = 0$$

Also, when $t = \frac{\pi}{2}$, $x = a$ and $y = 0$. Hence, the equation of tangent to the given curve at $t = \frac{\pi}{2}$, i.e., at $(a, 0)$ is

$$y - 0 = 0(x - a), \text{ i.e., } y = 0.$$

EXERCISE 6.3

- Find the slope of the tangent to the curve $y = x^4 - 4x$ at $x = 4$.
- Find the slope of the tangent to the curve $y = \frac{x-1}{x-2}$, $x \neq 2$ at $x = 10$.
- Find the slope of the tangent to curve $y = x^2 - x + 1$ at the point whose x -coordinate is 2.
- Find the slope of the tangent to the curve $y = x^2 - 2x + 2$ at the point whose x -coordinate is 2.
- Find the slope of the normal to the curve $x = a \cos^2 \theta$, $y = a \sin^2 \theta$ at $\theta = \frac{\pi}{4}$.
- Find the slope of the normal to the curve $x = 1 - a \sin \theta$, $y = b \cos^2 \theta$ at $\theta = \frac{\pi}{2}$.
- Find points at which the tangent to the curve $y = x^2 - 2x + 9$ is parallel to the x -axis.
- Find a point on the curve $y = (x - 1)^2$ at which the tangent is parallel to the chord joining the points $(0, 0)$ and $(4, 4)$.

9. Find the point on the curve $y = x^2 - 11x + 5$ at which the tangent is $y = x - 11$.
10. Find the equation of all lines having slope -1 that are tangents to the curve $y = \frac{1}{x-1}$, $x \neq 1$.
11. Find the equation of all lines having slope 1 which are tangents to the curve $y = \frac{1}{x-1}$, $x \neq 1$.
12. Find the equations of all lines having slope 0 which are tangent to the curve $y = \frac{1}{x^2 - 2x + 1}$.
13. Find points on the curve $\frac{x^2}{9} + \frac{y^2}{16} = 1$ at which the tangents are
 (i) parallel to x -axis (ii) parallel to y -axis.
14. Find the equations of the tangent and normal to the given curves at the indicated points
- $y = x^4 - 2x^3 + 1$ at $(0, 5)$
 - $y = x^4 - 2x^3 + 1$ at $(1, 1)$
 - $y = x^2$ at $(1, 1)$
 - $y = x^2$ at $(0, 0)$
 - $x = \cos t, y = \sin t$ at $t = \frac{\pi}{4}$
15. Find the equation of the tangent line to the curve $y = x^2 - 2x$ which is
 (a) parallel to the line $x - y - 9 = 0$
 (b) perpendicular to the line $5y - 15x = 1$
16. Show that the tangents to the curve $y = x^2 - 11$ at the points where $x = 1$ and $x = -1$ are parallel.
17. Find the points on the curve $y = x^2$ at which the slope of the tangent is equal to the y -coordinate of the point.
18. For the curve $y = 4x^2 - x^5$, find all the points at which the tangent passes through the origin.
19. Find the points on the curve $x^2 + y^2 - 2x - 2y = 0$ at which the tangents are parallel to the x -axis.
20. Find the equation of the normal at the point (am^2, am^3) for the curve $ay^2 = x^3$.

21. Find the equation of the normals to the curve $y = x^2 - 4x$ which are parallel to the line $x - 4y - 4 = 0$.
22. Find the equations of the tangent and normal to the parabola $y^2 = 4ax$ at the point $(at^2, 2at)$.
23. Prove that the curves $x = y^2$ and $xy = k$ cut at right angles if $k^2 = 1$.
24. Find the equations of the tangent and normal to the hyperbola $\frac{x^2}{a^2} - \frac{y^2}{b^2} = 1$ at the point (x_0, y_0) .
25. Find the equation of the tangent to the curve $y = \sqrt{x - 4}$ which is parallel to the line $4x - 3y + 5 = 0$.

Choose the correct answer in Exercises 26 and 27

26. The slope of the normal to the curve $y = x^2 \sin x$ at $x = 0$ is
 (A) $\frac{1}{2}$ (B) $\frac{1}{4}$ (C) $\frac{1}{8}$ (D) $-\frac{1}{4}$
27. The line $y = x - 1$ is a tangent to the curve $y^2 = 4x$ at the point
 (A) $(1, 1)$ (B) $(1, -1)$ (C) $(1, 2)$ (D) $(1, -2)$

6.5 Approximations

In this section, we will use differentials to approximate values of certain quantities.

Let $f: \mathbb{R} \rightarrow \mathbb{R}$, $a \in \mathbb{R}$, be a given function and let $y = f(x)$. Let Δx denote a small increment in x . Recall that the increment in y corresponding to the increment in x , denoted by Δy , is given by $\Delta y = f(x + \Delta x) - f(x)$. We define the following

- (i) The differential of x , denoted by dx , is defined by $dx = \Delta x$.
- (ii) The differential of y , denoted by dy , is defined by $dy = f'(x) dx$ or

$$dy = \left(\frac{dy}{dx} \right) \Delta x.$$

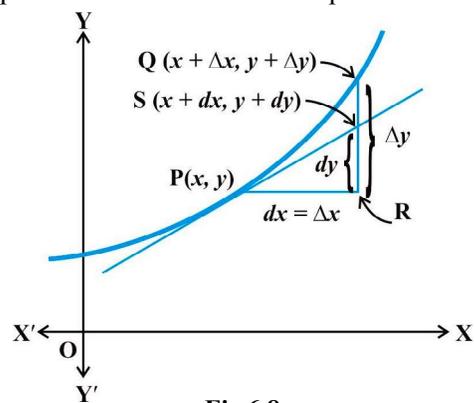


Fig 6.8

Two curves intersect at right angle if the tangents to the curves at the point of intersection are perpendicular to each other.

In case $dx = \Delta x$ is relatively small when compared with x , dy is a good approximation of Δy and we denote it by $dy \approx \Delta y$.

For geometrical meaning of Δx , Δy , dx and dy , one may refer to Fig 1.1

Note In view of the above discussion and Fig 1.1, we may note that the differential of the dependent variable is not equal to the increment of the variable where as the differential of independent variable is equal to the increment of the variable.

Example 21 Use differential to approximate $\sqrt{101}$.

Solution Take $y = \sqrt{x}$. Let $x = 100$ and let $\Delta x = 1$. Then

$$\Delta y = \sqrt{x + \Delta x} - \sqrt{x} = \sqrt{101} - \sqrt{100} = \sqrt{101} - 10$$

or $\sqrt{101} = 10 + \Delta y$

Now dy is approximately equal to Δy and is given by

$$dy = \left(\frac{dy}{dx} \right) \Delta x = \frac{1}{2\sqrt{x}} (1) = \frac{1}{2\sqrt{100}} (1) = 0.05 \quad (\text{as } y = \sqrt{x})$$

Thus, the approximate value of $\sqrt{101}$ is $10 + 0.05 = 10.05$.

Example 22 Use differential to approximate $(9.9)^{\frac{1}{3}}$.

Solution Let $y = x^{\frac{1}{3}}$. Let $x = 10$ and let $\Delta x = -0.1$. Then

$$\Delta y = (x + \Delta x)^{\frac{1}{3}} - x^{\frac{1}{3}} = (9.9)^{\frac{1}{3}} - (10)^{\frac{1}{3}} = (9.9)^{\frac{1}{3}} - 10^{\frac{1}{3}}$$

or $(9.9)^{\frac{1}{3}} = 10^{\frac{1}{3}} + \Delta y$

Now dy is approximately equal to Δy and is given by

$$\begin{aligned} dy &= \left(\frac{dy}{dx} \right) \Delta x = \frac{1}{3x^{\frac{2}{3}}} (-0.1) \quad (\text{as } y = x^{\frac{1}{3}}) \\ &= \frac{1}{3(10)^{\frac{2}{3}}} (-0.1) = \frac{-0.1}{30^{\frac{2}{3}}} = -0.004 \end{aligned}$$

Thus, the approximate value of $(9.9)^{\frac{1}{3}}$ is given by

$$10^{\frac{1}{3}} + (-0.004) = 2.154$$

Example 23 Find the approximate value of $f(1.01)$, where $f(x) = x^2 + 5x$

Solution Let $x = 1$ and $\Delta x = 0.01$. Then

$$f(1.01) = f(x + \Delta x) = (x + \Delta x)^2 + 5(x + \Delta x)$$

Note that $\Delta y = f(x + \Delta x) - f(x)$. Therefore

$$\begin{aligned} f(x + \Delta x) &= f(x) + \Delta y \\ &\approx f(x) + f'(x) \Delta x \quad (\text{as } dx = \Delta x) \end{aligned}$$

or

$$\begin{aligned} f(1.01) &\approx (1^2 + 5 \times 1) + (2 \times 1 + 5) \Delta x \\ &= (1 + 5) + (2 + 5)(0.01) \quad (\text{as } x = 1, \Delta x = 0.01) \\ &= (6 + 7)(0.01) \\ &= 6 + 0.07 = 6.07 \end{aligned}$$

Hence, approximate value of $f(1.01)$ is 6.07

Example 24 Find the approximate change in the volume V of a cube of side x meters caused by increasing the side by Δx .

Solution Note that

$$V = x^3$$

or

$$\begin{aligned} dV &= \left(\frac{dV}{dx} \right) \Delta x = (3x^2) \Delta x \\ &= (3x^2) (0.01x) = 0.03x^3 \text{ m}^3 \quad (\text{as } \Delta x \text{ of } x \text{ is } 0.01x) \end{aligned}$$

Thus, the approximate change in volume is $0.03x^3 \text{ m}^3$.

Example 25 If the radius of a sphere is measured as 9 cm with an error of 0.02 cm, then find the approximate error in calculating its volume.

Solution Let r be the radius of the sphere and Δr be the error in measuring the radius. Then $r = 9$ cm and $\Delta r = 0.02$ cm. Now, the volume V of the sphere is given by

$$V = \frac{4}{3} \pi r^3$$

or

$$\frac{dV}{dr} = 4\pi r^2$$

Therefore

$$\begin{aligned} dV &= \left(\frac{dV}{dr} \right) \Delta r = (4\pi r^2) \Delta r \\ &= 4\pi(9)^2 (0.02) = 9.8\pi \text{ cm}^3 \end{aligned}$$

Thus, the approximate error in calculating the volume is $9.8\pi \text{ cm}^3$.

EXERCISE 6.4

1. Using differentials, find the approximate value of each of the following up to 2 places of decimal.

(i) $\sqrt{15.1}$

(ii) $\sqrt{49.5}$

(iii) $\sqrt{0.9}$

(iv) $(0.009)^{\frac{1}{3}}$

(v) $(0.999)^{\frac{1}{10}}$

(vi) $(15)^{\frac{1}{4}}$

(vii) $(100)^{\frac{1}{3}}$

(viii) $(155)^{\frac{1}{4}}$

(ix) $(100)^{\frac{1}{4}}$

(x) $(401)^{\frac{1}{3}}$

(xi) $(0.001)^{\frac{1}{3}}$

(xii) $(150)^{\frac{1}{3}}$

(xiii) $(1.5)^{\frac{1}{4}}$

(xiv) $(900)^{\frac{1}{3}}$

(xv) $(15)^{\frac{1}{5}}$

2. Find the approximate value of $f(1.01)$, where $f(x) = 4x^2 + 5x + 1$.
3. Find the approximate value of $f(5.001)$, where $f(x) = x^3 + x^2 + 15$.
4. Find the approximate change in the volume V of a cube of side x metres caused by increasing the side by 1 cm.
5. Find the approximate change in the surface area of a cube of side x metres caused by decreasing the side by 1 cm.
6. If the radius of a sphere is measured as 10 cm with an error of 0.05 cm, then find the approximate error in calculating its volume.
7. If the radius of a sphere is measured as 9 m with an error of 0.05 m, then find the approximate error in calculating its surface area.
8. If $f(x) = x^3 + 15x + 5$, then the approximate value of $f(100)$ is
 (A) 4000 (B) 5000 (C) 1000 (D) 10000
9. The approximate change in the volume of a cube of side x metres caused by increasing the side by 1% is
 (A) $0.03x^3 \text{ m}^3$ (B) $0.01x^3 \text{ m}^3$ (C) $0.09x^3 \text{ m}^3$ (D) $0.9x^3 \text{ m}^3$

6.6 Maxima and Minima

In this section, we will use the concept of derivatives to calculate the maximum or minimum values of various functions. In fact, we will find the 'turning points' of the graph of a function and thus find points at which the graph reaches its highest (or

lowest) *locally*. The knowledge of such points is very useful in sketching the graph of a given function. Further, we will also find the absolute maximum and absolute minimum of a function that are necessary for the solution of many applied problems.

Let us consider the following problems that arise in day to day life.

- (i) The profit from a grove of orange trees is given by $P(x) = ax - bx^2$, where a, b are constants and x is the number of orange trees per acre. How many trees per acre will maximise the profit?
- (ii) A ball, thrown into the air from a building 10 metres high, travels along a path given by $h(x) = 10 + x - \frac{x^2}{10}$, where x is the horizontal distance from the building and $h(x)$ is the height of the ball. What is the maximum height the ball will reach?
- (iii) An Apache helicopter of enemy is flying along the path given by the curve $f(x) = x^2 - 2x + 1$. A soldier, placed at the point (1, 0), wants to shoot the helicopter when it is nearest to him. What is the nearest distance?

In each of the above problem, there is something common, i.e., we wish to find out the maximum or minimum values of the given functions. In order to tackle such problems, we first formally define maximum or minimum values of a function, points of local maxima and minima and test for determining such points.

Definition 3 Let f be a function defined on an interval I . Then

- (a) f is said to have a *maximum value* in I , if there exists a point c in I such that $f(c) > f(x)$, for all $x \in I$.

The number $f(c)$ is called the maximum value of f in I and the point c is called a *point of maximum value* of f in I .

- (b) f is said to have a *minimum value* in I , if there exists a point c in I such that $f(c) < f(x)$, for all $x \in I$.

The number $f(c)$, in this case, is called the minimum value of f in I and the point c , in this case, is called a *point of minimum value* of f in I .

- (c) f is said to have an *extreme value* in I if there exists a point c in I such that $f(c)$ is either a maximum value or a minimum value of f in I .

The number $f(c)$, in this case, is called an *extreme value* of f in I and the point c is called an *extreme point*.

Remark In Fig 9(a), (b) and (c), we have exhibited that graphs of certain particular functions help us to find maximum value and minimum value at a point. Infact, through graphs, we can even find maximum/minimum value of a function at a point at which it is not even differentiable (Example 1).

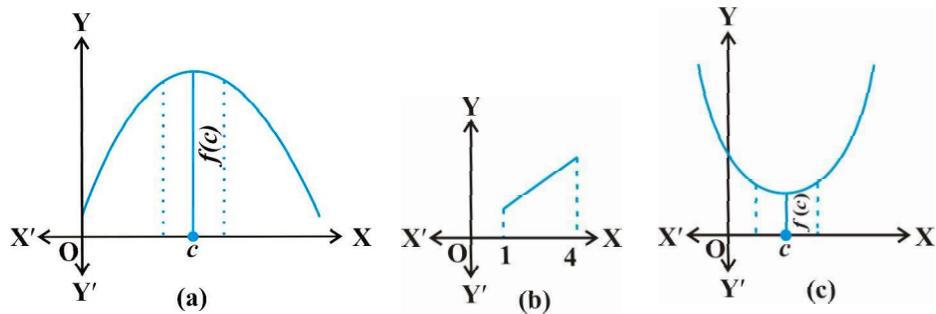


Fig 6.9

Example 26 Find the maximum and the minimum values, if any, of the function f given by

$$f(x) = x^2, x \in \mathbf{R}.$$

Solution From the graph of the given function (Fig 6.10), we have $f(x) = 0$ if $x = 0$. Also

$$f(x) \geq 0, \text{ for all } x \in \mathbf{R}.$$

Therefore, the minimum value of f is 0 and the point of minimum value of f is $x = 0$. Further, it may be observed from the graph of the function that f has no maximum value and hence no point of maximum value of f in \mathbf{R} .

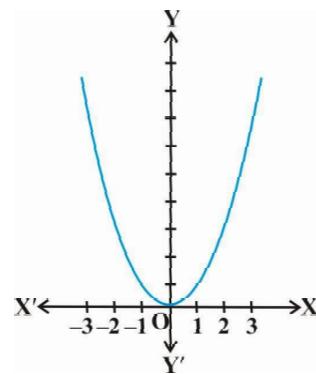


Fig 6.10

Note If we restrict the domain of f to $[-1, 1]$ only, then f will have maximum value $(1)^2 = 1$ at $x = 1$.

Example 27 Find the maximum and minimum values of f , if any, of the function given by $f(x) = |x|, x \in \mathbf{R}$.

Solution From the graph of the given function (Fig 6.11), note that

$$f(x) \geq 0, \text{ for all } x \in \mathbf{R} \text{ and } f(x) = 0 \text{ if } x = 0.$$

Therefore, the function f has a minimum value 0 and the point of minimum value of f is $x = 0$. Also, the graph clearly shows that f has no maximum value in \mathbf{R} and hence no point of maximum value in \mathbf{R} .

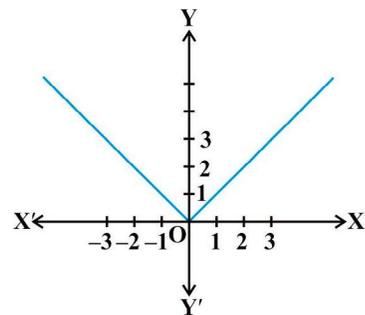


Fig 6.11

Note

(i) If we restrict the domain of f to $[-1, 1]$ only, then f will have maximum value 1 at $x = -1$ and $x = 1$.

(ii) One may note that the function f in Example 27 is not differentiable at $x = 0$.

Example 28 Find the maximum and the minimum values, if any, of the function given by

$$f(x) = x, x \in (0, 1).$$

Solution The given function is an increasing (strictly) function in the given interval $(0, 1)$. From the graph (Fig 6.12) of the function f , it seems that, it should have the minimum value at a point closest to 0 on its right and the maximum value at a point closest to 1 on its left. Are such points available? Of course, not. It is not possible to locate such points. In fact, if a point x_0 is closest to 0, then

we find $\frac{x_0}{2} < x_0$ for all $x_0 \in (0, 1)$. Also, if x_1 is

closest to 1, then $\frac{x_1 + 1}{2} > x_1$ for all $x_1 \in (0, 1)$.

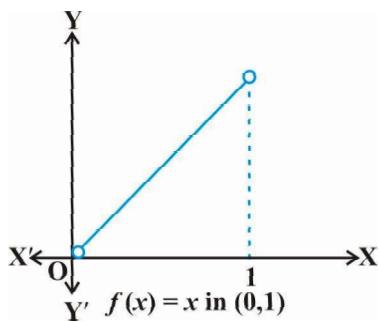


Fig 6.12

Therefore, the given function has neither the maximum value nor the minimum value in the interval $(0, 1)$.

Remark The reader may observe that in Example 27, if we include the points 0 and 1 in the domain of f , i.e., if we extend the domain of f to $[0, 1]$ then the function f has minimum value 0 at $x = 0$ and maximum value 1 at $x = 1$. In fact, we have the following results (The proof of these results are beyond the scope of the present text)

Every monotonic function assumes its maximum/minimum value at the end points of the domain of definition of the function.

A more general result is

Every continuous function on a closed interval has a maximum and a minimum value.

Note By a monotonic function f in an interval I , we mean that f is either increasing in I or decreasing in I .

Maximum and minimum values of a function defined on a closed interval will be discussed later in this section.

Let us now examine the graph of a function as shown in Fig 6.13. Observe that at points A, B, C and D on the graph, the function changes its nature from decreasing to increasing or vice-versa. These points may be called *turning points* of the given function. Further, observe that at turning points, the graph has either a little hill or a little valley. Roughly speaking, the function has minimum value in some neighbourhood (interval) of each of the points A and C which are at the bottom of their respective

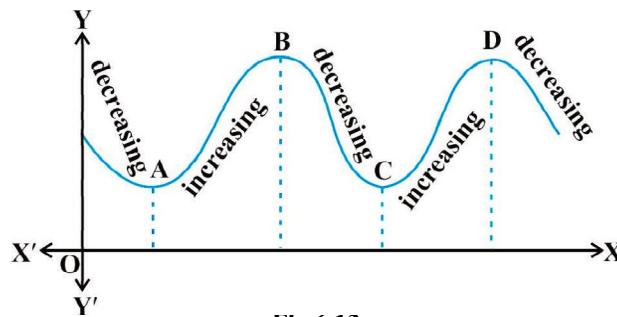


Fig 6.13

valleys. Similarly, the function has maximum value in some neighbourhood of points \square and \square which are at the top of their respective hills. For this reason, the points A and C may be regarded as points of *local minimum value* (or *relative minimum value*) and points \square and \square may be regarded as points of *local maximum value* (or *relative maximum value*) for the function. The *local maximum value* and *local minimum value* of the function are referred to as *local maxima* and *local minima*, respectively, of the function.

We now formally give the following definition

Definition 4 Let f be a real valued function and let c be an interior point in the domain of f . Then

- (a) c is called a point of *local maxima* if there is an $h > 0$ such that

$$f(c) > f(x), \text{ for all } x \text{ in } (c - h, c + h)$$

The value $f(c)$ is called the *local maximum value* of f .

- (b) c is called a point of *local minima* if there is an $h > 0$ such that

$$f(c) < f(x), \text{ for all } x \text{ in } (c - h, c + h)$$

The value $f(c)$ is called the *local minimum value* of f .

Geometrically, the above definition states that if $x = c$ is a point of local maxima of f , then the graph of f around c will be as shown in Fig 6.14(a). Note that the function f is increasing (i.e., $f'(x) > 0$) in the interval $(c - h, c)$ and decreasing (i.e., $f'(x) < 0$) in the interval $(c, c + h)$.

This suggests that $f'(c)$ must be zero.

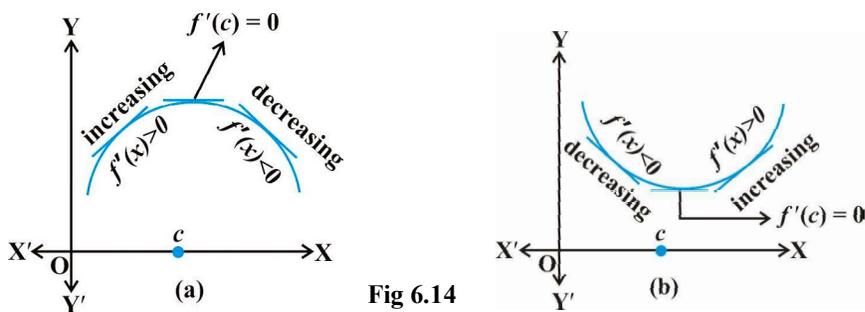


Fig 6.14

Similarly, if c is a point of local minima of f , then the graph of f around c will be as shown in Fig 6.14(b). Here f is decreasing (i.e., $f'(x) < 0$) in the interval $(c - h, c)$ and increasing (i.e., $f'(x) > 0$) in the interval $(c, c + h)$. This again suggest that $f'(c)$ must be zero.

The above discussion lead us to the following theorem (without proof).

Theorem 2 Let f be a function defined on an open interval I . Suppose $c \in I$ be any point. If f has a local maxima or a local minima at $x = c$, then either $f'(c) = 0$ or f is not differentiable at c .

Remark The converse of above theorem need not be true, that is, a point at which the derivative vanishes need not be a point of local maxima or local minima. For example, if $f(x) = x^3$, then $f'(x) = 3x^2$ and so $f'(0) = 0$. But 0 is neither a point of local maxima nor a point of local minima (Fig 6.15).

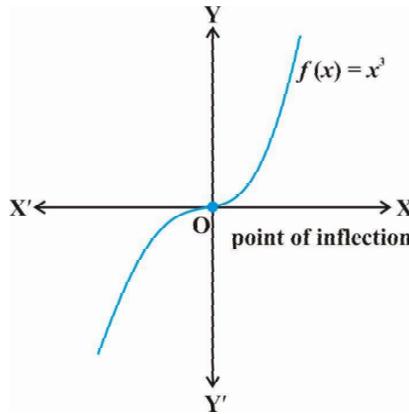


Fig 6.15

Note A point c in the domain of a function f at which either $f'(c) = 0$ or f is not differentiable is called a *critical point* of f . Note that if f is continuous at c and $f'(c) = 0$, then there exists an $h > 0$ such that f is differentiable in the interval $(c - h, c + h)$.

We shall now give a working rule for finding points of local maxima or points of local minima using only the first order derivatives.

Theorem 3 (First Derivative Test) Let f be a function defined on an open interval I . Let f be continuous at a critical point c in I . Then

- (i) If $f'(x)$ changes sign from positive to negative as x increases through c , i.e., if $f'(x) > 0$ at every point sufficiently close to and to the left of c , and $f'(x) < 0$ at every point sufficiently close to and to the right of c , then c is a point of *local maxima*.
- (ii) If $f'(x)$ changes sign from negative to positive as x increases through c , i.e., if $f'(x) < 0$ at every point sufficiently close to and to the left of c , and $f'(x) > 0$ at every point sufficiently close to and to the right of c , then c is a point of *local minima*.
- (iii) If $f'(x)$ does not change sign as x increases through c , then c is neither a point of local maxima nor a point of local minima. Infact, such a point is called *point of inflection* (Fig 6.15).

Note If c is a point of local maxima of f , then $f(c)$ is a local maximum value of f . Similarly, if c is a point of local minima of f , then $f(c)$ is a local minimum value of f .

Figures 6.15 and 6.16 geometrically explain Theorem 6.1

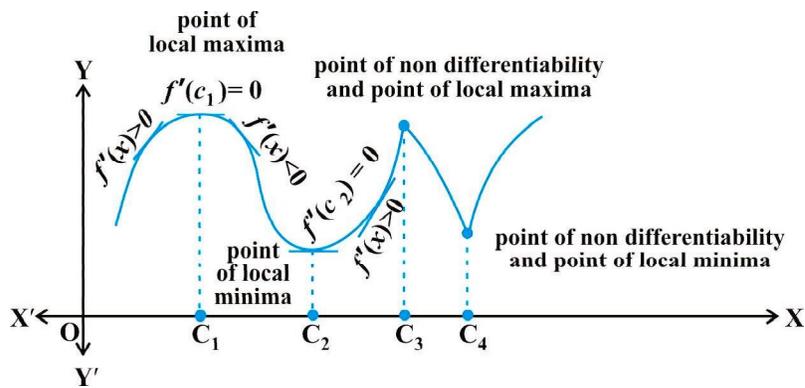


Fig 6.16

Example 29 Find all points of local maxima and local minima of the function f given by

$$f(x) = x^3 - 3x^2 + 4x - 5$$

Solution We have

$$f(x) = x^3 - 3x^2 + 4x - 5$$

or

$$f'(x) = 3x^2 - 6x + 4 = 3(x - 1)(x - \frac{2}{3})$$

or

$$f'(x) = 0 \text{ at } x = 1 \text{ and } x = \frac{2}{3}$$

Thus, $x = \frac{2}{3}$ and $x = 1$ are the only critical points which could possibly be the points of local maxima and/or local minima of f . Let us first examine the point $x = 1$.

Note that for values close to 1 and to the right of 1, $f'(x) < 0$ and for values close to 1 and to the left of 1, $f'(x) > 0$. Therefore, by first derivative test, $x = 1$ is a point of local minima and local minimum value is $f(1) = 1$. In the case of $x = \frac{2}{3}$, note that $f'(x) > 0$, for values close to and to the left of $\frac{2}{3}$ and $f'(x) < 0$, for values close to and to the right of $\frac{2}{3}$. Therefore, by first derivative test, $x = \frac{2}{3}$ is a point of local maxima and local maximum value is $f(\frac{2}{3}) = 5$.

Values of x	Sign of $f'(x) = 3(x - 1)(x + 1)$	
Close to 1	to the right (say 1.1 etc.)	< 0
	to the left (say 0.9 etc.)	> 0
Close to $\frac{2}{3}$	to the right (say $-\frac{1}{3}$ etc.)	< 0
	to the left (say $-\frac{1}{3}$ etc.)	> 0

Example 30 Find all the points of local maxima and local minima of the function f given by

$$f(x) = x^3 - x^2 - 5x + 5.$$

Solution We have

$$f(x) = x^3 - x^2 - 5x + 5$$

or

$$f'(x) = 3x^2 - 2x - 5 = (x - 1)(3x + 5)$$

or

$$f'(x) = 0 \quad \text{at } x = 1$$

Thus, $x = 1$ is the only critical point of f . We shall now examine this point for local maxima and/or local minima of f . Observe that $f'(x) \geq 0$, for all $x \in \mathbf{R}$ and in particular $f'(x) > 0$, for values close to 1 and to the left and to the right of 1. Therefore, by first derivative test, the point $x = 1$ is neither a point of local maxima nor a point of local minima. Hence $x = 1$ is a point of inflexion.

Remark One may note that since $f'(x)$, in Example 30, never changes its sign on \mathbf{R} , graph of f has no turning points and hence no point of local maxima or local minima.

We shall now give another test to examine local maxima and local minima of a given function. This test is often easier to apply than the first derivative test.

Theorem 4 (Second Derivative Test) Let f be a function defined on an interval I and $c \in I$. Let f be twice differentiable at c . Then

- (i) $x = c$ is a point of local maxima if $f'(c) = 0$ and $f''(c) < 0$

The value $f(c)$ is local maximum value of f .

- (ii) $x = c$ is a point of local minima if $f'(c) = 0$ and $f''(c) > 0$

In this case, $f(c)$ is local minimum value of f .

- (iii) The test fails if $f'(c) = 0$ and $f''(c) = 0$.

In this case, we go back to the first derivative test and find whether c is a point of local maxima, local minima or a point of inflexion.

Note As f is twice differentiable at c , we mean second order derivative of f exists at c .

Example 31 Find local minimum value of the function f given by $f(x) = |x|$, $x \in \mathbf{R}$.

Solution Note that the given function is not differentiable at $x = 0$. So, second derivative test fails. Let us try first derivative test. Note that 0 is a critical point of f . Now to the left of 0, $f(x) = -x$ and so $f'(x) = -1 < 0$. Also

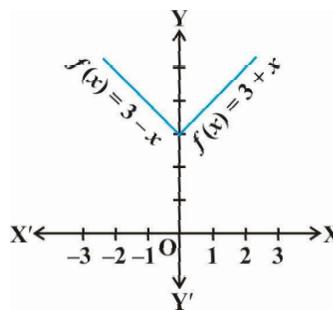


Fig 6.17

to the right of 0, $f(x) = x^2$ and so $f'(x) = 2x$. Therefore, by first derivative test, $x = 0$ is a point of local minima of f and local minimum value of f is $f(0) = 0$.

Example 32 Find local maximum and local minimum values of the function f given by

$$f(x) = x^4 - 4x^3 + 12x^2 - 12x + 1$$

Solution We have

$$f(x) = x^4 - 4x^3 + 12x^2 - 12x + 1$$

or

$$f'(x) = 4x^3 - 12x^2 + 24x - 12 = 4x(x - 1)(x - 1)$$

or

$$f'(x) = 0 \text{ at } x = 0, x = 1 \text{ and } x = 1$$

Now

$$f''(x) = 12x^2 - 24x + 12 = 12(x^2 - 2x + 1)$$

or

$$\begin{cases} f''(0) = -12 < 0 \\ f''(1) = 12 > 0 \\ f''(1) = 12 > 0 \end{cases}$$

Therefore, by second derivative test, $x = 0$ is a point of local maxima and local maximum value of f at $x = 0$ is $f(0) = 1$ while $x = 1$ and $x = 1$ are the points of local minima and local minimum values of f at $x = 1$ and $x = 1$ are $f(1) = 0$ and $f(1) = 0$, respectively.

Example 33 Find all the points of local maxima and local minima of the function f given by

$$f(x) = x^3 - 3x^2 + 3x - 5.$$

Solution We have

$$f(x) = x^3 - 3x^2 + 3x - 5$$

or

$$\begin{cases} f'(x) = 3x^2 - 6x + 3 = 3(x - 1)^2 \\ f''(x) = 6(x - 1) \end{cases}$$

Now $f'(x) = 0$ gives $x = 1$. Also $f''(1) = 0$. Therefore, the second derivative test fails in this case. So, we shall go back to the first derivative test.

We have already seen (Example 10) that, using first derivative test, $x = 1$ is neither a point of local maxima nor a point of local minima and so it is a point of inflexion.

Example 34 Find two positive numbers whose sum is 15 and the sum of whose squares is minimum.

Solution Let one of the numbers be x . Then the other number is $(15 - x)$. Let $S(x)$ denote the sum of the squares of these numbers. Then

$$S(x) = x^2 + (15 - x)^2 = x^2 + 0x + 225$$

or

$$\begin{cases} S'(x) = 4x - 30 \\ S''(x) = 4 \end{cases}$$

Now $S'(x) = 0$ gives $x = \frac{15}{2}$. Also $S''\left(\frac{15}{2}\right) = 4 > 0$. Therefore, by second derivative

test, $x = \frac{15}{2}$ is the point of local minima of S . Hence the sum of squares of numbers is

minimum when the numbers are $\frac{15}{2}$ and $15 - \frac{15}{2} = \frac{15}{2}$.

Remark Proceeding as in Example 34 one may prove that the two positive numbers, whose sum is k and the sum of whose squares is minimum, are $\frac{k}{2}$ and $\frac{k}{2}$.

Example 35 Find the shortest distance of the point $(0, c)$ from the parabola $y = x^2$, where $0 \leq c \leq 5$.

Solution Let (h, k) be any point on the parabola $y = x^2$. Let ϕ be the required distance between (h, k) and $(0, c)$. Then

$$\phi = \sqrt{(h-0)^2 + (k-c)^2} = \sqrt{h^2 + (k-c)^2} \quad \dots (1)$$

Since (h, k) lies on the parabola $y = x^2$, we have $k = h^2$. So (1) gives

$$\phi \equiv \phi(k) = \sqrt{k + (k-c)^2}$$

or

$$\phi'(k) = \frac{1 + 2(k-c)}{2\sqrt{k + (k-c)^2}}$$

Now

$$\phi'(k) = 0 \text{ gives } k = \frac{c-1}{2}$$

Observe that when $k < \frac{c-1}{2}$, then $2(k-c) + 1 < 0$, i.e., $\phi'(k) < 0$. Also when

$k > \frac{c-1}{2}$, then $\phi'(k) > 0$. So, by first derivative test, $\phi(k)$ is minimum at $k = \frac{c-1}{2}$.

Hence, the required shortest distance is given by

$$\frac{d}{dx} \left(\frac{c-1}{x} \right) = \sqrt{\frac{c-1}{x} + \left(\frac{c-1}{x} - c \right)^2} = \frac{\sqrt{4c-1}}{x}$$

Note The reader may note that in Example 35, we have used first derivative test instead of the second derivative test as the former is easy and short.

Example 36 Let AP and BQ be two vertical poles at points A and B , respectively. If $AP = 16$ m, $BQ = 22$ m and $AB = 20$ m, then find the distance of a point R on AB from the point A such that $RP + RQ$ is minimum.

Solution Let R be a point on AB such that $AR = x$ m. Then $RB = (20 - x)$ m (as $AB = 20$ m). From Fig 6.18 we have

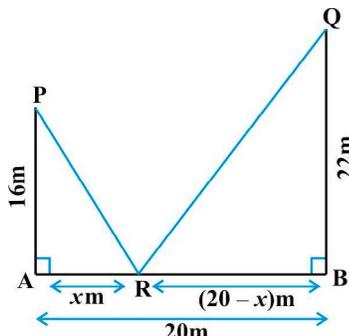


Fig 6.18

$$\begin{aligned} RP^2 &= AR^2 + AP^2 \\ RQ^2 &= RB^2 + BQ^2 \end{aligned}$$

and

$$\begin{aligned} RP + RQ &= \sqrt{AR^2 + AP^2} + \sqrt{RB^2 + BQ^2} \\ &= \sqrt{x^2 + (16)^2} + \sqrt{(20 - x)^2 + (22)^2} \\ &= \sqrt{x^2 + 40x + 1140} \end{aligned}$$

Let $S \equiv S(x) = RP + RQ = \sqrt{x^2 + 40x + 1140}$.

Therefore $S'(x) = \frac{4x + 40}{2\sqrt{x^2 + 40x + 1140}}$.

Now $S'(x) = 0$ gives $x = 10$. Also $S''(x) = \frac{4}{2\sqrt{x^2 + 40x + 1140}} > 0$, for all x and so $S''(10) > 0$. Therefore, by second derivative test, $x = 10$ is the point of local minima of S . Thus, the distance of R from A on AB is $AR = x = 10$ m.

Example 37 If length of three sides of a trapezium other than base are equal to 10 cm, then find the area of the trapezium when it is maximum.

Solution The required trapezium is as given in Fig 6.19. Draw perpendiculars DP and CQ

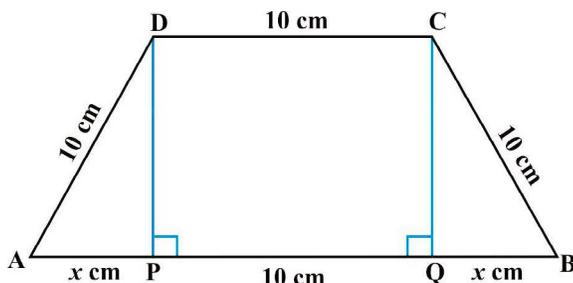


Fig 6.19

Let $AC = x$ cm. Note that $\triangle ABC \sim \triangle DEC$. Therefore, $DE = x$ cm. Also, by Pythagoras theorem, $DC = EC = \sqrt{100 - x^2}$. Let A be the area of the trapezium. Then

$$\begin{aligned} A &\equiv A(x) = \frac{1}{2} (\text{sum of parallel sides}) (\text{height}) \\ &= \frac{1}{2} (x + 10) (\sqrt{100 - x^2}) \\ &= (x + 10) (\sqrt{100 - x^2}) \end{aligned}$$

or

$$\begin{aligned} A'(x) &= (x + 10) \frac{(-2x)}{2\sqrt{100 - x^2}} + (\sqrt{100 - x^2}) \\ &= \frac{-2x^2 - 10x + 100}{\sqrt{100 - x^2}} \end{aligned}$$

Now $A'(x) = 0$ gives $-2x^2 - 10x + 100 = 0$, i.e., $x = 5$ and $x = -10$. Since x represents distance, it can not be negative.

So, $x = 5$. Now

$$\begin{aligned} A''(x) &= \frac{\sqrt{100 - x^2} (-4x - 10) - (-2x^2 - 10x + 100) \frac{(-2x)}{2\sqrt{100 - x^2}}}{100 - x^2} \\ &= \frac{-2x^3 - 100x - 1000}{(100 - x^2)^{3/2}} \quad (\text{on simplification}) \end{aligned}$$

or

$$A''(5) = \frac{-2(5)^3 - 100(5) - 1000}{(100 - (5)^2)^{3/2}} = \frac{-150}{5\sqrt{5}} = \frac{-30}{\sqrt{5}} < 0$$

Thus, area of trapezium is maximum at $x = 5$ and the area is given by

$$A(5) = (5 + 10) \sqrt{100 - (5)^2} = 15\sqrt{75} = 15\sqrt{3} \text{ cm}^2$$

Example 38 Prove that the radius of the right circular cylinder of greatest curved surface area which can be inscribed in a given cone is half of that of the cone.

Solution Let $OC = r$ be the radius of the cone and $OA = h$ be its height. Let a cylinder with radius $OE = x$ inscribed in the given cone (Fig 10.0). The height OE of the cylinder is given by

$$\frac{AE}{AB} = \frac{EC}{AC} \quad (\text{since } \triangle AEC \sim \triangle ABC)$$

or
$$\frac{AE}{h} = \frac{r-x}{r}$$

or
$$AE = \frac{h(r-x)}{r}$$

Let S be the curved surface area of the given cylinder. Then

$$S \equiv S(x) = \frac{2\pi x h(r-x)}{r} = \frac{2\pi h}{r} (rx - x^2)$$

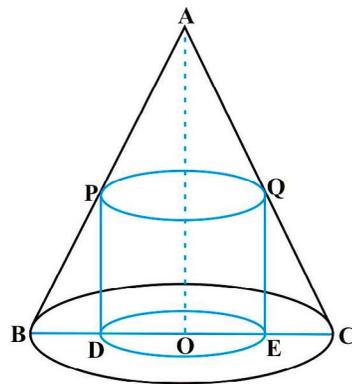


Fig 6.20

or
$$\begin{cases} S'(x) = \frac{2\pi h}{r} (r - 2x) \\ S''(x) = -\frac{4\pi h}{r} \end{cases}$$

Now $S'(x) = 0$ gives $x = \frac{r}{2}$. Since $S''(x) < 0$ for all x , $S''\left(\frac{r}{2}\right) < 0$. So $x = \frac{r}{2}$ is a

point of maxima of S . Hence, the radius of the cylinder of greatest curved surface area which can be inscribed in a given cone is half of that of the cone.

6.6.1 Maximum and Minimum Values of a Function in a Closed Interval

Let us consider a function f given by

$$f(x) = x^2, x \in (0, 1)$$

Observe that the function is continuous on $(0, 1)$ and neither has a maximum value nor has a minimum value. Further, we may note that the function even has neither a local maximum value nor a local minimum value.

However, if we extend the domain of f to the closed interval $[0, 1]$ then f still may not have a local maximum (minimum) values but it certainly does have maximum value $f(1)$ and minimum value $f(0)$. The maximum value $f(1)$ of f at $x = 1$ is called *absolute maximum value* (*global maximum* or *greatest value*) of f on the interval $[0, 1]$. Similarly, the minimum value $f(0)$ of f at $x = 0$ is called the *absolute minimum value* (*global minimum* or *least value*) of f on $[0, 1]$.

Consider the graph given in Fig 6.21 of a continuous function defined on a closed interval $[a, d]$. Observe that the function f has a local minima at $x = b$ and local

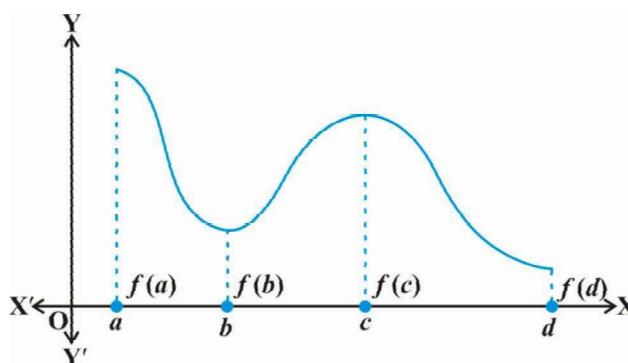


Fig 6.21

minimum value is $f(b)$. The function also has a local maxima at $x = c$ and local maximum value is $f(c)$.

Also from the graph, it is evident that f has absolute maximum value $f(a)$ and absolute minimum value $f(d)$. Further note that the absolute maximum (minimum) value of f is different from local maximum (minimum) value of f .

We will now state two results (without proof) regarding absolute maximum and absolute minimum values of a function on a closed interval I .

Theorem 5 Let f be a continuous function on an interval $I = [a, b]$. Then f has the absolute maximum value and f attains it at least once in I . Also, f has the absolute minimum value and attains it at least once in I .

Theorem 6 Let f be a differentiable function on a closed interval I and let c be any interior point of I . Then

- (i) $f'(c) = 0$ if f attains its absolute maximum value at c .
- (ii) $f'(c) = 0$ if f attains its absolute minimum value at c .

In view of the above results, we have the following working rule for finding absolute maximum and/or absolute minimum values of a function in a given closed interval $[a, b]$.

Working Rule

Step 1 Find all critical points of f in the interval, i.e., find points x where either $f'(x) = 0$ or f is not differentiable.

Step 2 Take the end points of the interval.

Step 3 At all these points (listed in Step 1 and 2), calculate the values of f .

Step 4 Identify the maximum and minimum values of f out of the values calculated in Step 3. This maximum value will be the absolute maximum (greatest) value of f and the minimum value will be the absolute minimum (least) value of f .

Example 39 Find the absolute maximum and minimum values of a function f given by

$$f(x) = x^3 - 15x^2 + 16x - 1 \text{ on the interval } [1, 5]$$

Solution We have

$$f(x) = x^3 - 15x^2 + 16x - 1$$

or
$$f'(x) = 3x^2 - 30x + 16 = (x - 1)(x - 16)$$

Note that $f'(x) = 0$ gives $x = 1$ and $x = 16$

We shall now evaluate the value of f at these points and at the end points of the interval $[1, 5]$ i.e., at $x = 1$, $x = 16$ and at $x = 5$. So

$$f(1) = (1)^3 - 15(1)^2 + 16(1) - 1 = -4$$

$$f(16) = (16)^3 - 15(16)^2 + 16(16) - 1 = 9$$

$$f(5) = (5)^3 - 15(5)^2 + 16(5) - 1 = -5$$

$$f(5) = (5)^3 - 15(5)^2 + 16(5) - 1 = -5$$

Thus, we conclude that absolute maximum value of f on $[1, 5]$ is 9 , occurring at $x = 16$, and absolute minimum value of f on $[1, 5]$ is -5 which occurs at $x = 5$.

Example 40 Find absolute maximum and minimum values of a function f given by

$$f(x) = 1 - x^{\frac{4}{3}} - x^{\frac{1}{3}}, x \in [0, 1]$$

Solution We have

$$f(x) = 1 - x^{\frac{4}{3}} - x^{\frac{1}{3}}$$

or
$$f'(x) = 1 - \frac{4}{3}x^{\frac{1}{3}} - \frac{1}{3}x^{-\frac{2}{3}} = \frac{3(1 - x - 1)}{3x^{\frac{2}{3}}}$$

Thus, $f'(x) = 0$ gives $x = \frac{1}{3}$. Further note that $f'(x)$ is not defined at $x = 0$. So the critical points are $x = 0$ and $x = \frac{1}{3}$. Now evaluating the value of f at critical points

$x = 0, \frac{1}{3}$ and at end points of the interval $x = 0$ and $x = 1$, we have

$$f(1) = 1 - (-1)^{\frac{4}{3}} - (-1)^{\frac{1}{3}} = 1 - 1 - (-1) = 1$$

$$f(0) = 1 - (0)^{\frac{4}{3}} - (0)^{\frac{1}{3}} = 0$$

$$f\left(\frac{1}{4}\right) = 1 - \left(\frac{1}{4}\right)^{\frac{4}{3}} - \left(\frac{1}{4}\right)^{\frac{1}{3}} = \frac{-9}{4}$$

$$f(1) = 1 - (1)^{\frac{4}{3}} - (1)^{\frac{1}{3}} = 0$$

Hence, we conclude that absolute maximum value of f is 1 that occurs at $x = 1$

and absolute minimum value of f is $\frac{-9}{4}$ that occurs at $x = \frac{1}{4}$.

Example 41 An Apache helicopter of enemy is flying along the curve given by $y = x^3$. A soldier, placed at $(1, 0)$, wants to shoot down the helicopter when it is nearest to him. Find the nearest distance.

Solution For each value of x , the helicopter's position is at point (x, x^3) . Therefore, the distance between the helicopter and the soldier placed at $(1, 0)$ is

$$\sqrt{(x-1)^2 + (x^3 - 0)^2}, \text{ i.e., } \sqrt{(x-1)^2 + x^6}.$$

Let $f(x) = (x-1)^2 + x^6$

or $f'(x) = 2(x-1) + 6x^5 = (2x-1) + 6x^5$

Thus, $f'(x) = 0$ gives $x = 1$ or $6x^5 + 2x - 1 = 0$ for which there are no real roots. Also, there are no end points of the interval to be added to the set for which f' is zero, i.e., there is only one point, namely, $x = 1$. The value of f at this point is given by $f(1) = (1-1)^2 + (1)^6 = 1$. Thus, the distance between the soldier and the helicopter is $\sqrt{f(1)} = \sqrt{1} = 1$.

Note that $\sqrt{1}$ is either a maximum value or a minimum value. Since

$$\sqrt{f(0)} = \sqrt{(0-1)^2 + (0)^6} = 1 > \sqrt{1},$$

it follows that $\sqrt{1}$ is the minimum value of $\sqrt{f(x)}$. Hence, $\sqrt{1}$ is the minimum distance between the soldier and the helicopter.

EXERCISE 6.5

1. Find the maximum and minimum values, if any, of the following functions given by

(i) $f(x) = (x-1)^2$

(ii) $f(x) = 9x^2 + 1/x$

(iii) $f(x) = (x-1)^2 + 10$

(iv) $g(x) = x^2 + 1$

2. Find the maximum and minimum values, if any, of the following functions given by

(i) $f(x) = x^2 - 1$

(ii) $g(x) = x^2 + 1$

(iii) $h(x) = \sin(x) + 5$

(iv) $f(x) = \sin 4x$

(v) $h(x) = x + 1, x \in (0, 1)$

3. Find the local maxima and local minima, if any, of the following functions. Find also the local maximum and the local minimum values, as the case may be

(i) $f(x) = x^3$

(ii) $g(x) = x^3 - x$

(iii) $h(x) = \sin x + \cos x, 0 < x < \frac{\pi}{2}$

(iv) $f(x) = \sin x + \cos x, 0 < x < \pi$

(v) $f(x) = x^3 - 9x^2 + 15x - 15$

(vi) $g(x) = \frac{x}{2} + \frac{1}{x}, x > 0$

(vii) $g(x) = \frac{1}{x^2 + 1}$

(viii) $f(x) = x\sqrt{1-x}, 0 < x < 1$

4. Prove that the following functions do not have maxima or minima

(i) $f(x) = e^x$

(ii) $g(x) = \log x$

(iii) $h(x) = x^3 + x^2 + x + 1$

5. Find the absolute maximum value and the absolute minimum value of the following functions in the given intervals

(i) $f(x) = x^2, x \in [0, 1]$

(ii) $f(x) = \sin x + \cos x, x \in [0, \pi]$

(iii) $f(x) = 4x - \frac{1}{2}x^2, x \in \left[-\frac{1}{2}, \frac{9}{2}\right]$

(iv) $f(x) = (x-1)^2 + 1, x \in [-1, 1]$

6. Find the maximum profit that a company can make, if the profit function is given by

$$p(x) = 41x - 1x^2$$

7. Find both the maximum value and the minimum value of

$$x^4 - x^3 + 1 - 4x + 5$$

on the interval $[0, 5]$

8. At what points in the interval $[0, \pi]$ does the function $\sin x$ attain its maximum value

9. What is the maximum value of the function $\sin x + \cos x$

10. Find the maximum value of $x^2 - 4x + 10$ in the interval $[1, 5]$. Find the maximum value of the same function in $[0, 1]$

11. It is given that at $x = 1$, the function $x^4 - x^3 - ax - 9$ attains its maximum value, on the interval $[0, \infty)$. Find the value of a .
12. Find the maximum and minimum values of $x \sin x$ on $[0, \pi]$.
13. Find two numbers whose sum is 4 and whose product is as large as possible.
14. Find two positive numbers x and y such that $x + y = 10$ and xy is maximum.
15. Find two positive numbers x and y such that their sum is 5 and the product x^2y^5 is a maximum.
16. Find two positive numbers whose sum is 1 and the sum of whose cubes is minimum.
17. A square piece of tin of side 1 cm is to be made into a box without top, by cutting a square from each corner and folding up the flaps to form the box. What should be the side of the square to be cut off so that the volume of the box is the maximum possible.
18. A rectangular sheet of tin 45 cm by 4 cm is to be made into a box without top, by cutting off square from each corner and folding up the flaps. What should be the side of the square to be cut off so that the volume of the box is maximum?
19. Show that of all the rectangles inscribed in a given fixed circle, the square has the maximum area.
20. Show that the right circular cylinder of given surface and maximum volume is such that its height is equal to the diameter of the base.
21. Of all the closed cylindrical cans (right circular), of a given volume of 100 cubic centimetres, find the dimensions of the can which has the minimum surface area.
22. A wire of length 1 m is to be cut into two pieces. One of the pieces is to be made into a square and the other into a circle. What should be the length of the two pieces so that the combined area of the square and the circle is minimum?
23. Prove that the volume of the largest cone that can be inscribed in a sphere of radius R is $\frac{8}{27}$ of the volume of the sphere.
24. Show that the right circular cone of least curved surface and given volume has an altitude equal to $\sqrt{3}$ times the radius of the base.
25. Show that the semi-vertical angle of the cone of the maximum volume and of given slant height is $\tan^{-1} \sqrt{3}$.
26. Show that semi-vertical angle of right circular cone of given surface area and maximum volume is $\sin^{-1} \left(\frac{1}{\sqrt{3}} \right)$.

Choose the correct answer in the Exercises 10 and 19.

27. The point on the curve $x^2 = 4y$ which is nearest to the point $(0, 5)$ is

- (A) $(\sqrt{4}, 4)$ (B) $(\sqrt{4}, 0)$ (C) $(0, 0)$ (D) $(1, 1)$

28. For all real values of x , the minimum value of $\frac{1-x+x^2}{1+x+x^2}$ is

- (A) 0 (B) 1 (C) $\frac{1}{2}$ (D) $\frac{1}{3}$

29. The maximum value of $x(x-1) + 1t^{\frac{1}{2}}$, $0 \leq x \leq 1$ is

- (A) $\left(\frac{1}{2}\right)^{\frac{1}{2}}$ (B) $\frac{1}{2}$ (C) 1 (D) 0

Miscellaneous Examples

Example 42 A car starts from a point A at time $t = 0$ seconds and stops at point B . The distance x , in metres, covered by it, in t seconds is given by

$$x = t^2 \left(1 - \frac{t}{4} \right)$$

Find the time taken by it to reach B and also find distance between A and B .

Solution Let v be the velocity of the car at t seconds.

Now
$$x = t^2 \left(1 - \frac{t}{4} \right)$$

Therefore
$$v = \frac{dx}{dt} = 4t - \frac{3}{4}t^2 = t(4 - \frac{3}{4}t)$$

Thus, $v = 0$ gives $t = 0$ and/or $t = 4$.

Now $v = 0$ at $t = 0$ as well as at $t = 4$ and at $t = 0$. So, at $t = 4$, the car will reach the point B after 4 seconds. Also the distance travelled in 4 seconds is given by

$$x_{t=4} = 4^2 \left(1 - \frac{4}{4} \right) = 16 \left(\frac{0}{4} \right) = \frac{16}{4} \text{ m}$$

Example 43 A water tank has the shape of an inverted right circular cone with its axis vertical and vertex lowermost. Its semi-vertical angle is $\tan^{-1}(0.5)$. Water is poured into it at a constant rate of 5 cubic metre per hour. Find the rate at which the level of the water is rising at the instant when the depth of water in the tank is 4 m.

Solution Let r , h and α be as in Fig 6.22. Then $\tan \alpha = \frac{r}{h}$.

So $\alpha = \tan^{-1}\left(\frac{r}{h}\right)$.
 But $\alpha = \tan^{-1}(0.5)$ (given)
 or $\frac{r}{h} = 0.5$
 or $r = \frac{h}{2}$

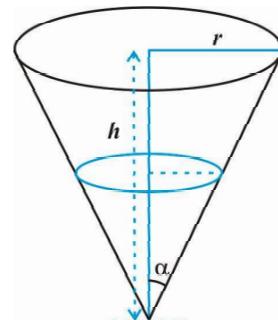


Fig 6.22

Let V be the volume of the cone. Then

$$V = \frac{1}{3} \pi r^2 h = \frac{1}{3} \pi \left(\frac{h}{2}\right)^2 h = \frac{\pi h^3}{12}$$

Therefore $\frac{dV}{dt} = \frac{d}{dh} \left(\frac{\pi h^3}{12} \right) \cdot \frac{dh}{dt}$ (by Chain Rule)

$$= \frac{\pi}{4} h^2 \frac{dh}{dt}$$

Now rate of change of volume, i.e., $\frac{dV}{dt} = 5 \text{ m}^3/\text{h}$ and $h = 4 \text{ m}$.

Therefore $5 = \frac{\pi}{4} (4)^2 \cdot \frac{dh}{dt}$

or $\frac{dh}{dt} = \frac{5}{4\pi} = \frac{5}{4\pi} \text{ m/h} \left(\pi = \frac{22}{7} \right)$

Thus, the rate of change of water level is $\frac{5}{4\pi} \text{ m/h}$.

Example 44 A man of height a metres walks at a uniform speed of 5 m/h away from a lamp post which is b metres high. Find the rate at which the length of his shadow increases.

Solution In Fig 6.23, let AB be the lamp post, the lamp being at the position B and let M be the man at a particular time t and let $AM = l$ metres. Then, MS is the shadow of the man. Let $MS = s$ metres.

Note that

$$\triangle MSN \sim \triangle ASB$$

or

$$\frac{MS}{AS} = \frac{MN}{AB}$$

or

$$AS = \frac{AB}{MN} \cdot MS \quad (\text{as } MN = h \text{ and } AB = H \text{ (given)})$$

Thus

$$AM = \frac{AB}{MN} \cdot s = \frac{H}{h} \cdot s. \quad \text{But } AM = l$$

So

$$l = \frac{H}{h} s$$

Therefore

$$\frac{dl}{dt} = \frac{H}{h} \frac{ds}{dt}$$

Since $\frac{ds}{dt} = 5$ m/h. Hence, the length of the shadow increases at the rate $\frac{5H}{h}$ m/h.

Example 45 Find the equation of the normal to the curve $x^2 = 4y$ which passes through the point $(1, 2)$.

Solution Differentiating $x^2 = 4y$ with respect to x , we get

$$\frac{dy}{dx} = \frac{x}{2}$$

Let (h, k) be the coordinates of the point of contact of the normal to the curve $x^2 = 4y$. Now, slope of the tangent at (h, k) is given by

$$\left. \frac{dy}{dx} \right|_{(h, k)} = \frac{h}{2}$$

Hence, slope of the normal at $(h, k) = -\frac{2}{h}$

Therefore, the equation of normal at (h, k) is

$$y - k = -\frac{2}{h}(x - h) \quad \dots (1)$$

Since it passes through the point $(1, 2)$, we have

$$2 - k = -\frac{2}{h}(1 - h) \quad \text{or} \quad k = 2 + \frac{2}{h}(1 - h) \quad \dots (2)$$

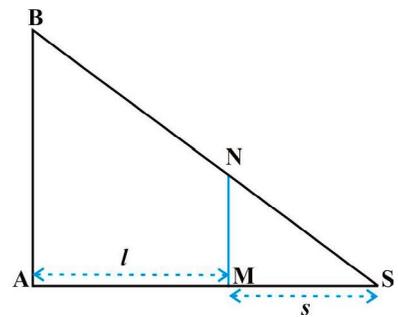


Fig 6.23

Since (h, k) lies on the curve $x^2 = 4y$, we have

$$h^2 = 4k \quad \dots (1)$$

From (1) and (2), we have $h = 2$ and $k = 1$. Substituting the values of h and k in (1), we get the required equation of normal as

$$y - 1 = \frac{-1}{2}(x - 2) \text{ or } x - y = 0$$

Example 46 Find the equation of tangents to the curve

$$y = \cos(x + y), \quad -\pi \leq x \leq \pi$$

that are parallel to the line $x - y = 0$.

Solution Differentiating $y = \cos(x + y)$ with respect to x , we have

$$\frac{dy}{dx} = \frac{-\sin(x + y)}{1 + \sin(x + y)}$$

or slope of tangent at $(x, y) = \frac{-\sin(x + y)}{1 + \sin(x + y)}$

Since the tangents to the given curve are parallel to the line $x - y = 0$, whose slope is $\frac{-1}{2}$, we have

$$\frac{-\sin(x + y)}{1 + \sin(x + y)} = \frac{-1}{2}$$

or $\sin(x + y) = 1$

or $x + y = n\pi + (-1)^n \frac{\pi}{2}, \quad n \in \mathbf{Z}$

Then $y = \cos(x + y) = \cos\left(n\pi + (-1)^n \frac{\pi}{2}\right), \quad n \in \mathbf{Z}$
 $= 0, \text{ for all } n \in \mathbf{Z}$

Also, since $-\pi \leq x \leq \pi$, we get $x = -\frac{\pi}{2}$ and $x = \frac{\pi}{2}$. Thus, tangents to the given curve are parallel to the line $x - y = 0$ only at points $\left(-\frac{\pi}{2}, 0\right)$ and $\left(\frac{\pi}{2}, 0\right)$. Therefore, the required equation of tangents are

$$y + 0 = \frac{-1}{4} \left(x + \frac{\pi}{4} \right) \quad \text{or} \quad x + 4y + \pi = 0$$

and

$$y + 0 = \frac{-1}{4} \left(x - \frac{\pi}{4} \right) \quad \text{or} \quad x + 4y - \pi = 0$$

Example 47 Find intervals in which the function given by

$$f(x) = \frac{1}{10}x^4 - \frac{4}{5}x^3 - x^2 + \frac{11}{5}x + 11$$

is (a) strictly increasing (b) strictly decreasing.

Solution We have

$$f(x) = \frac{1}{10}x^4 - \frac{4}{5}x^3 - x^2 + \frac{11}{5}x + 11$$

Therefore

$$\begin{aligned} f'(x) &= \frac{1}{10}(4x^3) - \frac{4}{5}(3x^2) - 2(x) + \frac{11}{5} \\ &= \frac{1}{5}(x-1)(x+2)(x-3) \quad (\text{on simplification}) \end{aligned}$$

Now $f'(x) = 0$ gives $x = 1, x = -2$ or $x = 3$. The points $x = 1, -2$ and 3 divide the real line into four disjoint intervals namely, $(-\infty, -2), (-2, 1), (1, 3)$ and $(3, \infty)$ (Fig 6.24).



Fig 6.24

Consider the interval $(-\infty, -2)$, i.e., when $-\infty < x < -2$

In this case, we have $x + 1 < 0, x + 2 < 0$ and $x - 3 < 0$.

(In particular, observe that for $x = -3, f'(x) = (x + 1)(x + 2)(x - 3) = (-2)(-1)(-6) = -12 < 0$)

Therefore, $f'(x) < 0$ when $-\infty < x < -2$

Thus, the function f is strictly decreasing in $(-\infty, -2)$.

Consider the interval $(-2, 1)$, i.e., when $-2 < x < 1$.

In this case, we have $x + 1 < 0, x + 2 > 0$ and $x - 3 < 0$

(In particular, observe that for $x = 0, f'(x) = (x + 1)(x + 2)(x - 3) = (1)(2)(-3) = -6 < 0$)

So $f'(x) < 0$ when $-2 < x < 1$.

Thus, f is strictly increasing in $(-2, 1)$.

Now consider the interval $(1, \infty)$, i.e., when $1 < x < \infty$. In this case, we have $x > 1 > 0$, $x > 0 > 0$ and $x > 0 > 0$.

So, $f'(x) > 0$ when $1 < x < \infty$.

Thus, f is strictly decreasing in $(1, \infty)$.

Finally, consider the interval $(-\infty, 0)$, i.e., when $x < 0$. In this case, we have $x < 1 < 0$, $x < 0 < 0$ and $x < 0 < 0$. So $f'(x) > 0$ when $x < 0$.

Thus, f is strictly increasing in the interval $(-\infty, 0)$.

Example 48 Show that the function f given by

$$f(x) = \tan^{-1}(\sin x + \cos x), \quad x \in \mathbb{R}$$

is always an strictly increasing function in $\left(0, \frac{\pi}{4}\right)$.

Solution We have

$$f(x) = \tan^{-1}(\sin x + \cos x), \quad x \in \mathbb{R}$$

Therefore

$$\begin{aligned} f'(x) &= \frac{1}{1 + (\sin x + \cos x)^2} (\cos x - \sin x) \\ &= \frac{\cos x - \sin x}{1 + \sin^2 x + \cos^2 x + 2 \sin x \cos x} \quad (\text{on simplification}) \end{aligned}$$

Note that $\cos x - \sin x > 0$ for all x in $\left(0, \frac{\pi}{4}\right)$.

Therefore $f'(x) > 0$ if $\cos x > \sin x > 0$

or $f'(x) > 0$ if $\cos x > \sin x$ or $\cot x > 1$

Now $\cot x > 1$ if $\tan x < 1$, i.e., if $0 < x < \frac{\pi}{4}$

Thus $f'(x) > 0$ in $\left(0, \frac{\pi}{4}\right)$

Hence f is strictly increasing function in $\left(0, \frac{\pi}{4}\right)$.

Example 49 A circular disc of radius r cm is being heated. Due to expansion, its radius increases at the rate of 0.05 cm/s . Find the rate at which its area is increasing when radius is 10 cm .

Solution Let r be the radius of the given disc and A be its area. Then

$$A = \pi r^2$$

or
$$\frac{dA}{dt} = 2\pi r \frac{dr}{dt} \quad (\text{by Chain Rule})$$

Now approximate rate of increase of radius = $dr = \frac{dr}{dt} \Delta t = 0.05 \text{ cm/s}$.

Therefore, the approximate rate of increase in area is given by

$$\begin{aligned} dA &= \frac{dA}{dt}(\Delta t) = 2\pi r \left(\frac{dr}{dt} \Delta t \right) \\ &= 2\pi(10)(0.05) = 0.628\pi \text{ cm}^2/\text{s} \quad (r = 10 \text{ cm}) \end{aligned}$$

Example 50 An open topped box is to be constructed by removing equal squares from each corner of a 12 metre by 8 metre rectangular sheet of aluminium and folding up the sides. Find the volume of the largest such box.

Solution Let x metre be the length of a side of the removed squares. Then, the height of the box is x , length is $8-2x$ and breadth is $3-2x$ (Fig 6.25). If $V(x)$ is the volume of the box, then

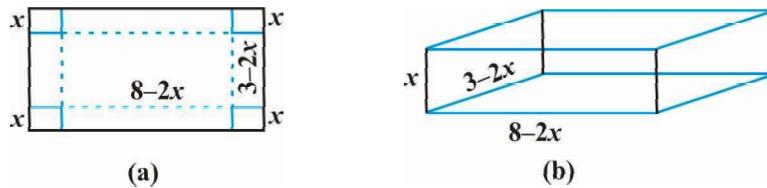


Fig 6.25

$$\begin{aligned} V(x) &= x(8-2x)(3-2x) \\ &= 4x^3 - 44x^2 + 24x \end{aligned}$$

Therefore
$$\begin{cases} V'(x) = 12x^2 - 44x + 24 = 4(x-1)(3x-2) \\ V''(x) = 24x - 44 \end{cases}$$

Now $V'(x) = 0$ gives $x = 1$ or $x = \frac{2}{3}$. But $x \neq 1$ (Why?)

Thus, we have $x = \frac{2}{3}$. Now $V''\left(\frac{2}{3}\right) = 24\left(\frac{2}{3}\right) - 44 = -\frac{40}{3} < 0$.

Therefore, $x = \frac{10}{3}$ is the point of maxima, i.e., if we remove a square of side $\frac{10}{3}$ metre from each corner of the sheet and make a box from the remaining sheet, then the volume of the box such obtained will be the largest and it is given by

$$\begin{aligned} V\left(\frac{10}{3}\right) &= 4\left(\frac{10}{3}\right)^3 - 4\left(\frac{10}{3}\right)^2 + 4\left(\frac{10}{3}\right) \\ &= \frac{100}{3} \text{ m}^3 \end{aligned}$$

Example 51 Manufacturer can sell x items at a price of rupees $\left(5 - \frac{x}{100}\right)$ each. The cost price of x items is Rs $\left(\frac{x}{5} + 500\right)$. Find the number of items he should sell to earn maximum profit.

Solution Let $S(x)$ be the selling price of x items and let $C(x)$ be the cost price of x items. Then, we have

$$S(x) = \left(5 - \frac{x}{100}\right)x = 5x - \frac{x^2}{100}$$

and
$$C(x) = \frac{x}{5} + 500$$

Thus, the profit function $P(x)$ is given by

$$P(x) = S(x) - C(x) = 5x - \frac{x^2}{100} - \frac{x}{5} - 500$$

i.e.
$$P(x) = \frac{4}{5}x - \frac{x^2}{100} - 500$$

or
$$P'(x) = \frac{4}{5} - \frac{x}{50}$$

Now $P'(x) = 0$ gives $x = 40$. Also $P''(x) = -\frac{1}{50}$. So $P''(40) = -\frac{1}{50} < 0$

Thus, $x = 40$ is a point of maxima. Hence, the manufacturer can earn maximum profit, if he sells 40 items.

Miscellaneous Exercise on Chapter 6

1. Using differentials, find the approximate value of each of the following

(a) $\left(\frac{1}{1}\right)^{\frac{1}{4}}$ (b) $(1)^{-\frac{1}{5}}$

2. Show that the function given by $f(x) = \frac{\log x}{x}$ has maximum at $x = e$.
3. The two equal sides of an isosceles triangle with fixed base b are decreasing at the rate of 1 cm per second. How fast is the area decreasing when the two equal sides are equal to the base

4. Find the equation of the normal to curve $x^2 = 4y$ which passes through the point $(1, 1)$.

5. Show that the normal at any point θ to the curve $x = a \cos \theta - a \theta \sin \theta, y = a \sin \theta + a \theta \cos \theta$ is at a constant distance from the origin.

6. Find the intervals in which the function f given by

$$f(x) = \frac{4 \sin x - x - x \cos x}{1 + \cos x}$$

is (i) strictly increasing (ii) strictly decreasing.

7. Find the intervals in which the function f given by $f(x) = x^2 + \frac{1}{x^2}, x \neq 0$ is

- (i) increasing (ii) decreasing.

8. Find the maximum area of an isosceles triangle inscribed in the ellipse $\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$ with its vertex at one end of the major axis.

9. A tank with rectangular base and rectangular sides, open at the top is to be constructed so that its depth is 1 m and volume is 8 m³. If building of tank costs Rs 10 per sq metres for the base and Rs 45 per square metre for sides. What is the cost of least expensive tank

10. The sum of the perimeter of a circle and square is k , where k is some constant. Prove that the sum of their areas is least when the side of square is double the radius of the circle.

11. A window is in the form of a rectangle surmounted by a semicircular opening. The total perimeter of the window is 10 m. Find the dimensions of the window to admit maximum light through the whole opening.
12. A point on the hypotenuse of a triangle is at distance a and b from the sides of the triangle.

Show that the maximum length of the hypotenuse is $(a^2 + b^2)^{\frac{1}{2}}$.

13. Find the points at which the function f given by $f(x) = (x - 1)^4 (x + 1)^2$ has
 (i) local maxima (ii) local minima
 (iii) point of inflexion

14. Find the absolute maximum and minimum values of the function f given by

$$f(x) = \cos^2 x - \sin x, x \in [0, \pi]$$

15. Show that the altitude of the right circular cone of maximum volume that can be inscribed in a sphere of radius r is $\frac{4r}{3}$.

16. Let f be a function defined on $[a, b]$ such that $f'(x) > 0$, for all $x \in (a, b)$. Then prove that f is an increasing function on (a, b) .

17. Show that the height of the cylinder of maximum volume that can be inscribed in a sphere of radius R is $\frac{4R}{3}$. Also find the maximum volume.

18. Show that height of the cylinder of greatest volume which can be inscribed in a right circular cone of height h and semi vertical angle α is one-third that of the cone and the greatest volume of cylinder is $\frac{4}{27} \pi h^3 \tan^3 \alpha$.

Choose the correct answer in the Exercises from 19 to 24.

19. A cylindrical tank of radius 10 m is being filled with wheat at the rate of 14 cubic metre per hour. Then the depth of the wheat is increasing at the rate of

- (A) 1 m/h (B) 0.1 m/h
 (C) 1.1 m/h (D) 0.5 m/h

20. The slope of the tangent to the curve $x = t^2 - 2t + 3, y = t^2 - 4t + 5$ at the point $(3, 1)$ is

- (A) $\frac{1}{2}$ (B) $\frac{1}{3}$ (C) $\frac{1}{4}$ (D) $-\frac{1}{2}$

21. The line $y = mx + 1$ is a tangent to the curve $y^2 = 4x$ if the value of m is
- (A) 1 (B) $\frac{1}{2}$ (C) $\frac{1}{4}$ (D) $\frac{1}{8}$
22. The normal at the point (1,1) on the curve $y = x^2$ is
- (A) $x + y = 0$ (B) $x - y = 0$
 (C) $x + y - 1 = 0$ (D) $x - y = 1$
23. The normal to the curve $x^2 = 4y$ passing (1,1) is
- (A) $x + y = 2$ (B) $x - y = 2$
 (C) $x + y = 1$ (D) $x - y = 1$
24. The points on the curve $9y^2 = x^2$, where the normal to the curve makes equal intercepts with the axes are
- (A) $\left(4, \pm \frac{1}{4}\right)$ (B) $\left(4, \frac{-1}{4}\right)$
 (C) $\left(4, \pm \frac{1}{2}\right)$ (D) $\left(\pm 4, \frac{1}{4}\right)$

Summary

- ◆ If a quantity y varies with another quantity x , satisfying some rule $y = f(x)$, then $\frac{dy}{dx}$ (or $f'(x)$) represents the rate of change of y with respect to x and $\left. \frac{dy}{dx} \right|_{x=x_0}$ (or $f'(x_0)$) represents the rate of change of y with respect to x at $x = x_0$.
- ◆ If two variables x and y are varying with respect to another variable t , i.e., if $x = f(t)$ and $y = g(t)$, then by Chain Rule

$$\frac{dy}{dx} = \frac{dy}{dt} \bigg/ \frac{dx}{dt}, \text{ if } \frac{dx}{dt} \neq 0.$$
- ◆ A function f is said to be
 - (a) increasing on an interval (a, b) if $x_1 < x_2$ in $(a, b) \Rightarrow f(x_1) \leq f(x_2)$ for all $x_1, x_2 \in (a, b)$.

Alternatively, if $f'(x) \geq 0$ for each x in (a, b)

(b) decreasing on (a, b) if

$$x_1 < x_2 \text{ in } (a, b) \Rightarrow f(x_1) \geq f(x_2) \text{ for all } x_1, x_2 \in (a, b).$$

Alternatively, if $f'(x) \leq 0$ for each x in (a, b)

- ◆ The equation of the tangent at (x_0, y_0) to the curve $y = f(x)$ is given by

$$y - y_0 = \left. \frac{dy}{dx} \right|_{(x_0, y_0)} (x - x_0)$$

- ◆ If $\frac{dy}{dx}$ does not exist at the point (x_0, y_0) , then the tangent at this point is parallel to the y -axis and its equation is $x = x_0$.

- ◆ If tangent to a curve $y = f(x)$ at $x = x_0$ is parallel to x -axis, then $\left. \frac{dy}{dx} \right|_{x=x_0} = 0$.

- ◆ Equation of the normal to the curve $y = f(x)$ at a point (x_0, y_0) is given by

$$y - y_0 = \frac{-1}{\left. \frac{dy}{dx} \right|_{(x_0, y_0)}} (x - x_0)$$

- ◆ If $\frac{dy}{dx}$ at the point (x_0, y_0) is zero, then equation of the normal is $x = x_0$.

- ◆ If $\frac{dy}{dx}$ at the point (x_0, y_0) does not exist, then the normal is parallel to x -axis and its equation is $y = y_0$.

- ◆ Let $y = f(x)$, Δx be a small increment in x and Δy be the increment in y corresponding to the increment in x , i.e., $\Delta y = f(x + \Delta x) - f(x)$. Then dy given by

$$dy = f'(x)dx \text{ or } dy = \left(\frac{dy}{dx} \right) \Delta x.$$

is a good approximation of Δy when $dx = \Delta x$ is relatively small and we denote it by $dy \approx \Delta y$.

- ◆ A point c in the domain of a function f at which either $f'(c) = 0$ or f is not differentiable is called a *critical point* of f .

◆ **First Derivative Test** Let f be a function defined on an open interval I . Let f be continuous at a critical point c in I . Then

- (i) If $f'(x)$ changes sign from positive to negative as x increases through c , i.e., if $f'(x) > 0$ at every point sufficiently close to and to the left of c , and $f'(x) < 0$ at every point sufficiently close to and to the right of c , then c is a point of *local maxima*.
- (ii) If $f'(x)$ changes sign from negative to positive as x increases through c , i.e., if $f'(x) < 0$ at every point sufficiently close to and to the left of c , and $f'(x) > 0$ at every point sufficiently close to and to the right of c , then c is a point of *local minima*.
- (iii) If $f'(x)$ does not change sign as x increases through c , then c is neither a point of local maxima nor a point of local minima. Infact, such a point is called *point of inflexion*.

◆ **Second Derivative Test** Let f be a function defined on an interval I and $c \in I$. Let f be twice differentiable at c . Then

- (i) $x = c$ is a point of local maxima if $f'(c) = 0$ and $f''(c) < 0$
The values $f(c)$ is local maximum value of f .
- (ii) $x = c$ is a point of local minima if $f'(c) = 0$ and $f''(c) > 0$
In this case, $f(c)$ is local minimum value of f .
- (iii) The test fails if $f'(c) = 0$ and $f''(c) = 0$.
In this case, we go bac to the first derivative test and find whether c is a point of maxima, minima or a point of inflexion.

◆ Working rule for finding absolute maxima and/or absolute minima

Step 1: Find all critical points of f in the interval, i.e., find points x where either $f'(x) = 0$ or f is not differentiable.

Step 2: Take the end points of the interval.

Step 3: At all these points (listed in Step 1 and 2), calculate the values of f .

Step 4: Identify the maximum and minimum values of f out of the values calculated in Step 3. This maximum value will be the absolute maximum value of f and the minimum value will be the absolute minimum value of f .

