

ES202 - Assignment Solutions

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1 Introduction

These are my solutions to the assignment given in the course ES202.

1.1 AI Policy of This Paper

Large-Language-Model's (LLM) are only used in the formatting of this file. At no point, LLM's are used to solve the questions in the assignment, unlike other students taking the course who like to ask the help of LLMs even during the examinations. The reason this is written in LaTeX rather than by hand, is only because I have no time to do it by hand, and wanted to improve my LaTeX skills. The git commit history can be found in the GitHub repository [jayshozie/es202-assignment](https://github.com/jayshozie/es202-assignment), also as a proof of the fact that this entire document was written by hand.

2 Question 1

Problem An airplane is monitored at coordinates $(5, 7, 4)$ relative to the airport (South, East, Up). Find the directional angles of the plane.

Solution: Let the position vector of the plane be \vec{r} . We define the axes such that $x = \text{South}$, $y = \text{East}$, and $z = \text{Up}$.

$$\begin{aligned}\vec{r} &= 5\hat{i} + 7\hat{j} + 4\hat{k} \\ \|\vec{r}\| &= \sqrt{5^2 + 7^2 + 4^2} \\ &= \sqrt{25 + 49 + 16} \\ &= \sqrt{90} \\ &\approx 9.4868\end{aligned}$$

The directional angles α, β, γ are given by the direction cosines:

$$\begin{aligned}\alpha &= \cos^{-1} \left(\frac{r_x}{\|\vec{r}\|} \right) & \beta &= \cos^{-1} \left(\frac{r_y}{\|\vec{r}\|} \right) & \gamma &= \cos^{-1} \left(\frac{r_z}{\|\vec{r}\|} \right) \\ &= \cos^{-1} \left(\frac{5}{\sqrt{90}} \right) & &= \cos^{-1} \left(\frac{7}{\sqrt{90}} \right) & &= \cos^{-1} \left(\frac{4}{\sqrt{90}} \right) \\ &\approx 58.19^\circ & &\approx 42.45^\circ & &\approx 64.06^\circ\end{aligned}$$

3 Question 2

Problem Prove that $\|\vec{a} \cdot \vec{b}\| \leq \|\vec{a}\| \cdot \|\vec{b}\|$

Solution By the geometric definition of the dot product, the angle θ between the vectors $\|\vec{a}\|$ and $\|\vec{b}\|$ is given by:

$$\vec{a} \cdot \vec{b} = \|\vec{a}\| \|\vec{b}\| \cos \theta$$

We know that for any real angle θ , the cosine function is bounded:

$$-1 \leq \cos \theta \leq 1 \implies \|\cos \theta\| \leq 1$$

Substituting this inequality back into our original equation:

$$\|\vec{a} \cdot \vec{b}\| = \|\vec{a}\| \cdot \|\vec{b}\| \underbrace{\|\cos \theta\|}_{\leq 1}$$

Therefore proving:

$$\|\vec{a} \cdot \vec{b}\| \leq \|\vec{a}\| \cdot \|\vec{b}\| \quad (1)$$

4 Question 3

Problem Prove $\|\vec{a} + \vec{b}\| \leq \|\vec{a}\| + \|\vec{b}\|$

Solution Since magnitudes are non-negative by definition, proving the inequality is equivalent to proving it for the squares of the magnitudes. Consider the square of the sum:

$$\begin{aligned}\|\vec{a} + \vec{b}\|^2 &= (\vec{a} + \vec{b}) \cdot (\vec{a} + \vec{b}) \\ &= \vec{a} \cdot \vec{a} + 2(\vec{a} \cdot \vec{b}) + \vec{b} \cdot \vec{b} \\ &= \|\vec{a}\|^2 + 2(\vec{a} \cdot \vec{b}) + \|\vec{b}\|^2\end{aligned}$$

From (1) ([Cauchy-Schwartz Inequality](#)), we established that

$$\vec{a} \cdot \vec{b} \leq \|\vec{a} \cdot \vec{b}\| \leq \|\vec{a}\| \|\vec{b}\|$$

We substitute this upper bound into the equation:

$$\|\vec{a} + \vec{b}\|^2 \leq \|\vec{a}\|^2 + 2\|\vec{a}\| \|\vec{b}\| + \|\vec{b}\|^2$$

Recognizing the right-hand side as a perfect expansion $(x+y)^2 = x^2 + 2xy + y^2$:

$$\|\vec{a} + \vec{b}\|^2 \leq \left(\|\vec{a}\| + \|\vec{b}\| \right)^2$$

Taking the square root of both sides, which is valid since magnitudes are non-negative:

$$\|\vec{a} + \vec{b}\| \leq \|\vec{a}\| + \|\vec{b}\| \tag{2}$$

5 Question 4

Problem Prove $\|\vec{a} \times \vec{b}\|^2 = \|\vec{a}\|^2 \|\vec{b}\|^2 - (\vec{a} \cdot \vec{b})^2$

Solution Magnitude of the vector-product of two vectors \vec{a} and \vec{b} , separated by an angle θ , is defined as:

$$\|\vec{a} \times \vec{b}\| = \|\vec{a}\| \|\vec{b}\| \sin \theta \quad (3)$$

Square both sides:

$$\begin{aligned} \|\vec{a} \times \vec{b}\|^2 &= (\|\vec{a}\| \|\vec{b}\| \sin \theta)^2 \\ &= \|\vec{a}\|^2 \|\vec{b}\|^2 \sin^2 \theta \end{aligned}$$

Since,

$$\begin{aligned} \cos^2 \theta + \sin^2 \theta &= 1 \\ \sin^2 \theta &= 1 - \cos^2 \theta \end{aligned}$$

By substituting that to our original equality's right-hand side, we get:

$$\|\vec{a} \times \vec{b}\|^2 = \|\vec{a}\|^2 \|\vec{b}\|^2 (1 - \cos^2 \theta)$$

Then, by distributing $\|\vec{a}\|^2 \|\vec{b}\|^2$, we get:

$$= \|\vec{a}\|^2 \|\vec{b}\|^2 - \|\vec{a}\|^2 \|\vec{b}\|^2 \cos^2 \theta$$

Observe that,

$$\|\vec{a}\|^2 \|\vec{b}\|^2 \cos^2 \theta = (\|\vec{a}\| \|\vec{b}\| \sin \theta)^2 = (\vec{a} \cdot \vec{b})^2$$

Thus, by substituting that, we complete our proof:

$$\|\vec{a} \times \vec{b}\|^2 = \|\vec{a}\|^2 \|\vec{b}\|^2 - (\vec{a} \cdot \vec{b})^2 \quad (4)$$

6 Question 5

Problem Let vectors $\vec{u}_1 = (1, 0, 0)$, $\vec{u}_2 = (1, 1, 0)$, and $\vec{u}_3 = (1, 1, 1)$ form a basis for the vector space \mathbb{R}^3 . Show that these vectors are linearly independent and express vector $\vec{a} = (3, -4, 8)$ as a linear combination of them.

Solution We will divide our solution to two parts. In the first part, we'll prove that the given vectors \vec{u}_1 , \vec{u}_2 , and \vec{u}_3 are linearly independent, thus forming a basis for \mathbb{R}^3 ; then we'll find a linear combination for the vector \vec{a} .

Part 1: Linear Independence We form a matrix A with the vectors \vec{u}_1 , \vec{u}_2 , and \vec{u}_3 as columns. The vectors are linearly independent if $\det(A) \neq 0$.

$$\det(A) = \begin{vmatrix} 1 & 1 & 1 \\ 0 & 1 & 1 \\ 0 & 0 & 1 \end{vmatrix}$$

Since this is an upper-triangular matrix, the determinant is the product of the diagonal entries:

$$\det(A) = 1 \cdot 1 \cdot 1 = 1 \neq 0$$

Therefore, the vectors are linearly independent and form a basis for \mathbb{R}^3 .

Part 2: Linear Combination We wish to find coefficients c_1 , c_2 , and c_3 such that:

$$c_1 \cdot \vec{u}_1 + c_2 \cdot \vec{u}_2 + c_3 \cdot \vec{u}_3 = \vec{a}$$

This corresponds to the linear system:

$$\left[\begin{array}{ccc|c} 1 & 1 & 1 & 3 \\ 0 & 1 & 1 & -4 \\ 0 & 0 & 1 & 8 \end{array} \right]$$

Using back-substitution:

1. $c_3 = 8$
2. $c_2 + 8 = -4 \implies c_2 = -12$
3. $c_1 + (-12) + 8 = 3 \implies c_1 - 4 = 3 \implies c_1 = 7$

Using those coefficients, we can say that:

$$\vec{a} = 7\vec{u}_1 - 12\vec{u}_2 + 8\vec{u}_3$$

7 Question 6

Problem Obtain an orthonormal set from the given set of vectors using Gram-Schmidt Orthogonalization Process:

$$\vec{B} = \left\{ \left(\frac{1}{2}, \frac{1}{2}, 1 \right) \left(-1, 1, -\frac{1}{2} \right) \left(-1, \frac{1}{2}, 1 \right) \right\}$$

Solution Let the given vectors be \vec{v}_1 , \vec{v}_2 , and \vec{v}_3 . We will generate an orthogonal set $\{\vec{u}_1, \vec{u}_2, \vec{u}_3\}$ and then normalize them to get the orthonormal set $\{\vec{e}_1, \vec{e}_2, \vec{e}_3\}$.

Step 1. Process the first vector To use the Gram-Schmidt Orthogonalization Process, we need to pick a vector. For convention, we'll pick \vec{v}_1 as our first vector.

$$\vec{u}_1 = \vec{v}_1 = \left(\frac{1}{2}, \frac{1}{2}, 1 \right)$$

Calculating the magnitude of \vec{u}_1 gives us:

$$\begin{aligned} \|\vec{u}_1\| &= \sqrt{\left(\frac{1}{2}\right)^2 + \left(\frac{1}{2}\right)^2 + 1^2} \\ &= \sqrt{\frac{3}{2}} \end{aligned}$$

So, our first orthonormal vector \vec{e}_1 is:

$$\begin{aligned} \vec{e}_1 &= \frac{\vec{u}_1}{\|\vec{u}_1\|} \\ &= \sqrt{\frac{2}{3}} \left(\frac{1}{2}, \frac{1}{2}, 1 \right) \end{aligned}$$

Step 2. Orthogonalize the second vector We calculate the projection of \vec{u}_2 onto \vec{u}_1 .

$$\begin{aligned} \vec{v}_2 \cdot \vec{u}_1 &= (-1) \left(\frac{1}{2} \right) + (1) \left(\frac{1}{2} \right) + \left(-\frac{1}{2} \right) (1) = -\frac{1}{2} \\ \vec{u}_2 &= \vec{v}_2 - \frac{\vec{v}_2 \cdot \vec{u}_1}{\|\vec{u}_1\|^2} \vec{u}_1 = \left(-1, 1, -\frac{1}{2} \right) - \frac{-1/2}{3/2} \left(\frac{1}{2}, \frac{1}{2}, 1 \right) \\ &= \left(-1, 1, -\frac{1}{2} \right) + \frac{1}{3} \left(\frac{1}{2}, \frac{1}{2}, 1 \right) = \left(-\frac{5}{6}, \frac{7}{6}, -\frac{1}{6} \right) \end{aligned}$$

We, then, normalize \vec{u}_2 by:

$$\|\vec{u}_2\|^2 = \frac{25}{36} + \frac{49}{36} + \frac{1}{36} = \frac{75}{36} = \frac{25}{12} \implies \|\vec{u}_2\| = \frac{5}{2\sqrt{3}}$$

$$\vec{e}_2 = \frac{\vec{u}_2}{\|\vec{u}_2\|} = \frac{2\sqrt{3}}{5} \left(-\frac{5}{6}, \frac{7}{6}, -\frac{1}{6} \right) = \left(-\frac{\sqrt{3}}{3}, \frac{7\sqrt{3}}{15}, -\frac{\sqrt{3}}{15} \right)$$

Step 3: Orthogonalize the third vector Formula: $\vec{u}_3 = \vec{v}_3 - \text{proj}_{\vec{u}_1}(\vec{v}_3) - \text{proj}_{\vec{u}_2}(\vec{v}_3)$. First, we compute the projection coefficients:

$$\frac{\vec{v}_3 \cdot \vec{u}_1}{\|\vec{u}_1\|^2} = \frac{(-1)(\frac{1}{2}) + (\frac{1}{2})(\frac{1}{2}) + (1)(1)}{3/2} = \frac{3/4}{3/2} = \frac{1}{2}$$

$$\frac{\vec{v}_3 \cdot \vec{u}_2}{\|\vec{u}_2\|^2} = \frac{(-1)(-\frac{5}{6}) + (\frac{1}{2})(\frac{7}{6}) + (1)(-\frac{1}{6})}{25/12} = \frac{\frac{5}{6} + \frac{7}{12} - \frac{2}{12}}{25/12} = \frac{15/12}{25/12} = \frac{3}{5}$$

Now substitute back to find \vec{u}_3 :

$$\begin{aligned} \vec{u}_3 &= \vec{v}_3 - \frac{1}{2}\vec{u}_1 - \frac{3}{5}\vec{u}_2 \\ &= \left(-1, \frac{1}{2}, 1 \right) - \left(\frac{1}{4}, \frac{1}{4}, \frac{1}{2} \right) - \left(-\frac{1}{2}, \frac{7}{10}, -\frac{1}{10} \right) \\ &= (-1 - 0.25 + 0.5, 0.5 - 0.25 - 0.7, 1 - 0.5 + 0.1) \\ &= (-0.75, -0.45, 0.6) = \left(-\frac{3}{4}, -\frac{9}{20}, \frac{3}{5} \right) \end{aligned}$$

Normalize \vec{u}_3 :

$$\|\vec{u}_3\|^2 = \frac{9}{16} + \frac{81}{400} + \frac{9}{25} = \frac{225 + 81 + 144}{400} = \frac{450}{400} = \frac{9}{8}$$

$$\vec{e}_3 = \frac{\vec{u}_3}{\sqrt{9/8}} = \frac{2\sqrt{2}}{3} \left(-\frac{3}{4}, -\frac{9}{20}, \frac{3}{5} \right) = \left(-\frac{\sqrt{2}}{2}, -\frac{3\sqrt{2}}{10}, \frac{2\sqrt{2}}{5} \right)$$

Final Answer: The orthonormal set is $\{\vec{e}_1, \vec{e}_2, \vec{e}_3\}$, where:

$$\begin{aligned} \vec{e}_1 &= \left(\frac{\sqrt{2}}{2\sqrt{3}}, \frac{\sqrt{2}}{2\sqrt{3}}, \frac{\sqrt{2}}{\sqrt{3}} \right) \\ \vec{e}_2 &= \left(-\frac{\sqrt{3}}{3}, \frac{7\sqrt{3}}{15}, -\frac{\sqrt{3}}{15} \right) \\ \vec{e}_3 &= \left(-\frac{\sqrt{2}}{2}, -\frac{3\sqrt{2}}{10}, \frac{2\sqrt{2}}{5} \right) \end{aligned}$$

8 Question 7

Problem Verify that the matrix A satisfies its own characteristic equation

$$A = \begin{bmatrix} 1 & -2 \\ 4 & 5 \end{bmatrix}$$

Solution

Step 1. Find the Characteristic Equation The characteristic equation of a matrix is given by $\det(A - \lambda I) = 0$.

$$\begin{aligned}\det(A - \lambda I) &= \begin{vmatrix} 1 - \lambda & -2 \\ 4 & 5 - \lambda \end{vmatrix} \\ &= (1 - \lambda)(5 - \lambda) - (-2)(4) \\ &= (5 - \lambda - 5\lambda + \lambda^2) - (-8) \\ &= \lambda^2 - 6\lambda + 5 + 8 \\ &= \lambda^2 - 6\lambda + 13\end{aligned}$$

Thus, the characteristic equation is $\lambda^2 - 6\lambda + 13 = 0$.

Step 2. Verify for Matrix A According to the Cayley-Hamilton theorem, the matrix A should satisfy:

$$A^2 - 6A + 13I = 0$$

First, we calculate A^2 :

$$\begin{aligned}A^2 &= \begin{bmatrix} 1 & -2 \\ 4 & 5 \end{bmatrix} \begin{bmatrix} 1 & -2 \\ 4 & 5 \end{bmatrix} \\ &= \begin{bmatrix} (1)(1) + (-2)(4) & (1)(-2) + (-2)(5) \\ (4)(1) + (5)(4) & (4)(-2) + (5)(5) \end{bmatrix} \\ &= \begin{bmatrix} 1 - 8 & -2 - 10 \\ 4 + 20 & -8 + 25 \end{bmatrix} = \begin{bmatrix} -7 & -12 \\ 24 & 17 \end{bmatrix}\end{aligned}$$

Now, we substitute A^2 and A into the equation:

$$\begin{aligned}A^2 - 6A + 13I &= \begin{bmatrix} -7 & -12 \\ 24 & 17 \end{bmatrix} - 6 \begin{bmatrix} 1 & -2 \\ 4 & 5 \end{bmatrix} + 13 \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \\ &= \begin{bmatrix} -7 & -12 \\ 24 & 17 \end{bmatrix} - \begin{bmatrix} 6 & -12 \\ 24 & 30 \end{bmatrix} + \begin{bmatrix} 13 & 0 \\ 0 & 13 \end{bmatrix} \\ &= \begin{bmatrix} -7 - 6 + 13 & -12 - (-12) + 0 \\ 24 - 24 + 0 & 17 - 30 + 13 \end{bmatrix} \\ &= \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}\end{aligned}$$

The result is the zero matrix, verifying that A satisfies its own characteristic equation.

9 Question 8

Problem Compute $A^m : A = \begin{bmatrix} -1 & 2 \\ 0 & -3 \end{bmatrix}$, $m = 6$.

Solution We will compute A^6 by diagonalizing the matrix. We find matrices P and D such that $A = PDP^{-1}$, which implies $A^6 = PD^6P^{-1}$.

Step 1. Find Eigenvalues Since A is an upper triangular matrix, its eigenvalues are the diagonal entries:

$$\lambda_1 = -1, \quad \lambda_2 = -3$$

Step 2. Find Eigenvectors

For $\lambda_1 = -1$:

$$(A - (-1)I)\vec{v}_1 = \begin{bmatrix} 0 & 2 \\ 0 & -2 \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

From row 1:

$$2y = 0 \implies y = 0$$

x is a free variable, so we choose

$$\vec{v}_1 = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

For $\lambda_2 = -3$:

$$(A - (-3)I)\vec{v}_2 = \begin{bmatrix} 2 & 2 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

From row 1:

$$2x + 2y = 0 \implies x = -y$$

Let $y = 1$, then $x = -1$. We choose

$$\vec{v}_2 = \begin{bmatrix} -1 \\ 1 \end{bmatrix}$$

Step 3: Construct Matrices P and D The matrix P consists of the eigenvectors, and D contains the eigenvalues:

$$P = \begin{bmatrix} 1 & -1 \\ 0 & 1 \end{bmatrix}, \quad D = \begin{bmatrix} -1 & 0 \\ 0 & -3 \end{bmatrix}$$

We need to find to have the final diagonalization formula P^{-1} . Observe that the determinant of P is $(1)(1) - (-1)(0) = 1$.

$$P^{-1} = \frac{1}{1} \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix}$$

Step 4: Compute A^6 Using the diagonalization formula:

$$\begin{aligned} A^6 &= PD^6P^{-1} \\ &= \begin{bmatrix} 1 & -1 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} (-1)^6 & 0 \\ 0 & (-3)^6 \end{bmatrix} \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix} \\ &= \begin{bmatrix} 1 & -1 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & 729 \end{bmatrix} \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix} \\ &= \begin{bmatrix} 1 & -729 \\ 0 & 729 \end{bmatrix} \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix} \\ &= \begin{bmatrix} 1(1) + (-729)(0) & 1(1) + (-729)(1) \\ 0(1) + 729(0) & 0(1) + 729(1) \end{bmatrix} \\ &= \begin{bmatrix} 1 & -728 \\ 0 & 729 \end{bmatrix} \end{aligned}$$

10 Question 9

Problem Determine whether the given matrix A is diagonalizable. If so, find the matrix P that diagonalizes A , and the diagonal matrix D such that $D = P^{-1}AP$.

Solution

Step 1. Find Eigenvalues We solve the characteristic equation $\det(A - \lambda I) = 0$:

$$\begin{aligned} \begin{vmatrix} -\lambda & 5 \\ 1 & -\lambda \end{vmatrix} &= 0 \\ (-\lambda)(-\lambda) - (5)(1) &= 0 \\ \lambda^2 - 5 &= 0 \implies \lambda = \pm\sqrt{5} \end{aligned}$$

Since there are two distinct real eigenvalues, the matrix is diagonalizable. Let $\lambda_1 = \sqrt{5}$ and $\lambda_2 = -\sqrt{5}$.

Step 2. Find Eigenvectors

For $\lambda_1 = \sqrt{5}$:

$$(A - \sqrt{5}I)\vec{v}_1 = \begin{bmatrix} -\sqrt{5} & 5 \\ 1 & -\sqrt{5} \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

From the second row:

$$1x - \sqrt{5}y = 0 \implies x = \sqrt{5}y$$

Let $y = 1$, then $x = \sqrt{5}$. We choose the eigenvector \vec{v}_1 corresponding to the eigenvalue λ_1 as:

$$\vec{v}_1 = \begin{bmatrix} \sqrt{5} \\ 1 \end{bmatrix}$$

For $\lambda_2 = -\sqrt{5}$:

$$(A - (-\sqrt{5})I)\vec{v}_2 = \begin{bmatrix} \sqrt{5} & 5 \\ 1 & \sqrt{5} \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

From the second row:

$$1x + \sqrt{5}y = 0 \implies x = -\sqrt{5}y$$

Let $y = 1$, then $x = -\sqrt{5}$. We choose the eigenvector \vec{v}_2 corresponding to the eigenvalue λ_2 as:

$$\vec{v}_2 = \begin{bmatrix} -\sqrt{5} \\ 1 \end{bmatrix}$$

Step 3. Construct Matrices P and D The diagonal matrix D contains the eigenvalues, and P contains the corresponding eigenvectors as columns.

$$D = \begin{bmatrix} \sqrt{5} & 0 \\ 0 & -\sqrt{5} \end{bmatrix}, \quad P = \begin{bmatrix} \sqrt{5} & -\sqrt{5} \\ 1 & 1 \end{bmatrix}$$

So, the matrix A is diagonalizable with the matrices P and D given above.

11 Question 10

Problem Find a basis for i) column space, ii) row space, iii) null space of matrix A :

$$A = \begin{bmatrix} 0 & 6 & 6 & 0 \\ 1 & 2 & 1 & 1 \\ 0 & 1 & -3 & 4 \\ 1 & 0 & 2 & 0 \end{bmatrix}$$

Solution To find the bases, we perform Gaussian Elimination to reduce matrix A to Row Echelon Form (REF).

Step 1. Row Reduction Swap R_1 and R_2 to get a pivot in the first column:

$$\xrightarrow{R_1 \leftrightarrow R_2} \begin{bmatrix} 1 & 2 & 1 & 1 \\ 0 & 6 & 6 & 0 \\ 0 & 1 & -3 & 4 \\ 1 & 0 & 2 & 0 \end{bmatrix}$$

Eliminate the entry in R_4 using R_1 ($R_4 \rightarrow R_4 - R_1$):

$$\xrightarrow{R_4 - R_1} \begin{bmatrix} 1 & 2 & 1 & 1 \\ 0 & 6 & 6 & 0 \\ 0 & 1 & -3 & 4 \\ 0 & -2 & 1 & -1 \end{bmatrix}$$

Simplify R_2 by dividing by 6 ($R_2 \rightarrow \frac{1}{6}R_2$):

$$\xrightarrow{\frac{1}{6}R_2} \begin{bmatrix} 1 & 2 & 1 & 1 \\ 0 & 1 & 1 & 0 \\ 0 & 1 & -3 & 4 \\ 0 & -2 & 1 & -1 \end{bmatrix}$$

Eliminate entries below the second pivot ($R_3 \rightarrow R_3 - R_2$ and $R_4 \rightarrow R_4 + 2R_2$):

$$\begin{bmatrix} 1 & 2 & 1 & 1 \\ 0 & 1 & 1 & 0 \\ 0 & 0 & -4 & 4 \\ 0 & 0 & 3 & -1 \end{bmatrix}$$

Simplify R_3 ($R_3 \rightarrow -\frac{1}{4}R_3$) to get pivot 1:

$$\xrightarrow{-\frac{1}{4}R_3} \begin{bmatrix} 1 & 2 & 1 & 1 \\ 0 & 1 & 1 & 0 \\ 0 & 0 & 1 & -1 \\ 0 & 0 & 3 & -1 \end{bmatrix}$$

Eliminate the entry in R_4 ($R_4 \rightarrow R_4 - 3R_3$):

$$\xrightarrow{R_4 - 3R_3} \begin{bmatrix} 1 & 2 & 1 & 1 \\ 0 & 1 & 1 & 0 \\ 0 & 0 & 1 & -1 \\ 0 & 0 & 0 & 2 \end{bmatrix} : \text{REF}$$

Now that the matrix is in **Row Echelon Form**, we have pivots in columns 1, 2, 3, and 4. Since there are 4 pivots for a 4×4 matrix, the matrix has Full Rank (Rank = 4).

i) Basis for Column Space The basis for the column space consists of the pivot columns from the **original** matrix A . Since all columns have pivots:

$$\text{Basis}_{Col} = \left\{ \begin{pmatrix} 0 \\ 1 \\ 0 \\ 1 \end{pmatrix}, \begin{pmatrix} 6 \\ 2 \\ 1 \\ 0 \end{pmatrix}, \begin{pmatrix} 6 \\ 1 \\ -3 \\ 2 \end{pmatrix}, \begin{pmatrix} 0 \\ 1 \\ 4 \\ 0 \end{pmatrix} \right\}$$

ii) Basis for Row Space The basis for the row space consists of the non-zero rows of the **Row Echelon Form**:

$$\text{Basis}_{Row} = \{(1, 2, 1, 1), (0, 1, 1, 0), (0, 0, 1, -1), (0, 0, 0, 1)\}$$

iii) Basis for Null Space The null space is found by solving $A\vec{x} = \vec{0}$. Since the matrix is full rank, there are no free variables. The only solution is the trivial solution $\vec{x} = \vec{0}$.

$$\text{Null Space} = \{\vec{0}\}$$

The dimension of the null space is 0, so the basis is the empty set \emptyset .

12 Question 11

Problem Obtain an orthonormal set from the given set of vectors using Gram-Schmidt Orthogonalization Process.

$$\vec{V}_1 = (1, 0, 1), \quad \vec{V}_2 = (1, 1, 0), \quad \vec{V}_3 = (1, -2, -3)$$

Solution We generate an orthogonal set $\{\vec{u}_1, \vec{u}_2, \vec{u}_3\}$ and then normalize to get $\{\vec{e}_1, \vec{e}_2, \vec{e}_3\}$.

Step 1. Process first vector

Set $\vec{u}_1 = \vec{V}_1 = (1, 0, 1)$.

$$\|\vec{u}_1\|^2 = 1^2 + 0^2 + 1^2 = 2 \implies \|\vec{u}_1\| = \sqrt{2}$$

The first orthonormal vector is:

$$\vec{e}_1 = \frac{\vec{u}_1}{\sqrt{2}} = \left(\frac{1}{\sqrt{2}}, 0, \frac{1}{\sqrt{2}} \right)$$

Step 2. Orthogonalize second vector

Calculate projection of \vec{V}_2 onto \vec{u}_1 :

$$\begin{aligned} \vec{V}_2 \cdot \vec{u}_1 &= (1)(1) + (1)(0) + (0)(1) = 1 \\ \vec{u}_2 &= \vec{V}_2 - \frac{\vec{V}_2 \cdot \vec{u}_1}{\|\vec{u}_1\|^2} \vec{u}_1 \\ &= (1, 1, 0) - \frac{1}{2}(1, 0, 1) \\ &= (1, 1, 0) - (0.5, 0, 0.5) \\ &= (0.5, 1, -0.5) = \left(\frac{1}{2}, 1, -\frac{1}{2} \right) \end{aligned}$$

Normalize \vec{u}_2 :

$$\begin{aligned} \|\vec{u}_2\|^2 &= \left(\frac{1}{2} \right)^2 + 1^2 + \left(-\frac{1}{2} \right)^2 = \frac{1}{4} + 1 + \frac{1}{4} = \frac{3}{2} \\ \|\vec{u}_2\| &= \sqrt{\frac{3}{2}} \\ \vec{e}_2 &= \frac{\vec{u}_2}{\sqrt{3/2}} = \sqrt{\frac{2}{3}} \left(\frac{1}{2}, 1, -\frac{1}{2} \right) = \left(\frac{1}{\sqrt{6}}, \frac{2}{\sqrt{6}}, -\frac{1}{\sqrt{6}} \right) \end{aligned}$$

Step 3. Orthogonalize third vector

Formula: $\vec{u}_3 = \vec{V}_3 - \text{proj}_{\vec{u}_1}(\vec{V}_3) - \text{proj}_{\vec{u}_2}(\vec{V}_3)$. First, compute the dot products:

$$\vec{V}_3 \cdot \vec{u}_1 = (1)(1) + (-2)(0) + (-3)(1) = 1 - 3 = -2$$

$$\vec{V}_3 \cdot \vec{u}_2 = (1)(0.5) + (-2)(1) + (-3)(-0.5) = 0.5 - 2 + 1.5 = 0$$

Since $\vec{V}_3 \cdot \vec{u}_2 = 0$, the vector \vec{V}_3 is already orthogonal to \vec{u}_2 , so the second projection term is zero.

$$\begin{aligned}\vec{u}_3 &= \vec{V}_3 - \frac{-2}{2}\vec{u}_1 - 0 \\ &= (1, -2, -3) - (-1)(1, 0, 1) \\ &= (1, -2, -3) + (1, 0, 1) \\ &= (2, -2, -2)\end{aligned}$$

Normalize \vec{u}_3 :

$$\begin{aligned}\|\vec{u}_3\| &= \sqrt{2^2 + (-2)^2 + (-2)^2} = \sqrt{4 + 4 + 4} = \sqrt{12} = 2\sqrt{3} \\ \vec{e}_3 &= \frac{(2, -2, -2)}{2\sqrt{3}} = \frac{(1, -1, -1)}{\sqrt{3}} = \left(\frac{1}{\sqrt{3}}, -\frac{1}{\sqrt{3}}, -\frac{1}{\sqrt{3}}\right)\end{aligned}$$

The orthonormal set is $\{\vec{e}_1, \vec{e}_2, \vec{e}_3\}$, where

$$\vec{e}_1 = \left(\frac{1}{\sqrt{2}}, 0, \frac{1}{\sqrt{2}}\right), \quad \vec{e}_2 = \left(\frac{1}{\sqrt{6}}, \frac{2}{\sqrt{6}}, \frac{1}{\sqrt{6}}\right), \quad \vec{e}_3 = \left(\frac{1}{\sqrt{3}}, -\frac{1}{\sqrt{3}}, -\frac{1}{\sqrt{3}}\right)$$

13 Question 12

Problem

- i) Given the force field $\vec{f} = (y+z)\hat{i} + y\hat{j} + 4x^2y\hat{k}$, is the field conservative?
ii) For $A\vec{x} = \vec{b}$, find the values of the real numbers "a and c" for which the following system of equations has;
- No Solution
 - Unique Solution
 - Parametric Solution
- d) Write the ranks of matrices $[A]$ and $[A|\vec{b}]$ for parts a, b, and c.

$$A = \begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & a \\ 1 & 1 & 2 \end{bmatrix}, \text{ and } \vec{b} = \begin{bmatrix} c \\ 1 \\ 2 \end{bmatrix}$$

Solution

i) Is the force field conservative?

A vector field \vec{f} is conservative if $\nabla \times \vec{f} = \vec{0}$. So, let us calculate the curl of that field:

$$\nabla \times \vec{f} = \begin{vmatrix} \hat{i} & \hat{j} & \hat{k} \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ (y+z) & y & 4x^2y \end{vmatrix}$$

Expanding the determinant, we get:

$$\begin{aligned} \hat{i}\text{-Component: } & \frac{\partial}{\partial y}(4x^2y) - \frac{\partial}{\partial z}(y) = 4x^2 - 0 = 4x^2 \\ \hat{j}\text{-Component: } & \frac{\partial}{\partial z}(y+z) - \frac{\partial}{\partial x}(4x^2y) = 1 - 8xy \\ \hat{k}\text{-Component: } & \frac{\partial}{\partial x}(y) - \frac{\partial}{\partial y}(y-z) = 0 - 1 = -1 \end{aligned}$$

The result is:

$$\nabla \times \vec{f} = (4x^2)\hat{i} + (1 - 8xy)\hat{j} - \hat{k} \neq \vec{0}$$

Since the curl of \vec{f} is not the zero vector, the force field is **not conservative**.

ii) System of Equations Analysis

We perform Gaussian Elimination on the augmented matrix $[A|\vec{b}]$ to find the **Row Echelon Form**.

Step 1. Row Reduction

$$[A|\vec{b}] = \left[\begin{array}{ccc|c} 0 & 1 & 1 & c \\ 1 & 0 & a & 1 \\ 1 & 1 & 2 & 2 \end{array} \right]$$

Swap R_1 and R_2 to get a pivot in the first column:

$$\xrightarrow{R_1 \leftrightarrow R_2} \left[\begin{array}{ccc|c} 1 & 0 & a & 1 \\ 0 & 1 & 1 & c \\ 1 & 1 & 2 & 2 \end{array} \right]$$

Eliminate the pivot in R_3 ($R_3 \rightarrow R_3 - R_1$):

$$\xrightarrow{R_3 - R_1} \left[\begin{array}{ccc|c} 1 & 0 & a & 1 \\ 0 & 1 & 1 & c \\ 0 & 1 & 2-a & 1 \end{array} \right]$$

Eliminate the entry in R_3 in column 2 ($R_3 \rightarrow R_3 - R_2$):

$$\xrightarrow{R_3 - R_2} \left[\begin{array}{ccc|c} 1 & 0 & a & 1 \\ 0 & 1 & 1 & c \\ 0 & 0 & 1-a & 1-c \end{array} \right]$$

The behavior of the system depends entirely on the pivot term $(1-a)$ and the result term $(1-c)$.

Analysis of Cases:

- a) No Solution** For this system to be inconsistent, we need a row of the form $[0\ 0\ 0\ | k]$ where $k \neq 0$.

$$1-a=0 \implies a=1, \quad \text{and} \quad 1-c \neq 0 \implies c \neq 1$$

Ranks: $r[A] = 2, r[A|\vec{b}] = 3$.

- b) Unique Solution** For a unique solution, we need full rank (3 pivots), meaning the term $(1-a)$ cannot be zero.

$$1-a \neq 0 \implies a \neq 1, \quad c \in \mathbb{R} \quad (c \text{ can be any real number})$$

Ranks: $r[A] = 3, r[A|\vec{b}] = 3$.

- c) Parametric Solution** For infinite solutions, we need a free variable, meaning the last row must be entirely zero $[0\ 0\ 0\ | 0]$.

$$1-a=0 \implies a=1, \quad \text{and} \quad 1-c=0 \implies c=1$$

Ranks: $r[A] = 2, r[A|\vec{b}] = 2$.

14 Question 13

Problem Compute A^m and use this result to compute the indicated power of the matrix A.

$$A = \begin{bmatrix} -2 & 2 & -1 \\ 2 & 1 & -2 \\ -3 & -6 & 0 \end{bmatrix} : m = 5$$

Solution We diagonalize the matrix as $A = PDP^{-1}$, which implies $A^5 = PD^5P^{-1}$.

Step 1. Find the Eigenvalues

The characteristic equation is:

$$\det(A - \lambda I) = \begin{bmatrix} -2 - \lambda & 2 & -1 \\ 2 & 1 - \lambda & -2 \\ -3 & -6 & -\lambda \end{bmatrix} = 0$$

Expanding along the first row:

$$\begin{aligned} &= (-2 - \lambda) [(1 - \lambda)(-\lambda) - (-2)(-6)] - 2 [2(-\lambda) - (-2)(-3)] + (-1) [2(-6) - (1 - \lambda)(-3)] \\ &= -(2 + \lambda) [-\lambda + \lambda^2 - 12] - 2 [-2\lambda - 6] - 1 [-12 + 3 - 3\lambda] \\ &= -(2 + \lambda)(\lambda^2 - \lambda - 12) + 4\lambda + 12 + 9 + 3\lambda \\ &= -(2\lambda^2 - 2\lambda - 24 + \lambda^3 - \lambda^2 - 12\lambda) + 7\lambda + 21 \\ &= -(\lambda^3 + \lambda^2 - 14\lambda - 24) + 7\lambda + 21 \\ &= -\lambda^3 - \lambda^2 + 14\lambda + 24 + 7\lambda + 21 \\ &= -\lambda^3 - \lambda^2 + 21\lambda + 45 = 0 \end{aligned}$$

Multiplying by -1 , we solve $\lambda^3 + \lambda^2 - 21\lambda - 45 = 0$. Testing integer roots (factors of 45), we find $\lambda = 5$:

$$(5)^3 + (5)^2 - 21(5) - 45 = 125 + 25 - 105 - 45 = 150 - 150 = 0$$

Thus $(\lambda - 5)$ is a factor. Performing polynomial division gives $(\lambda - 5)(\lambda + 3)^2 = 0$. The eigenvalues are $\lambda_1 = 5$ and $\lambda_{2,3} = -3$.

Step 2. Find Eigenvectors

Case 1. $\lambda = 5$

Solve $(A - 5I)\vec{v} = \vec{0}$:

$$\begin{bmatrix} -7 & 2 & -1 \\ 2 & -4 & -2 \\ -3 & -6 & -5 \end{bmatrix} \xrightarrow{R_2 \leftrightarrow R_1} \begin{bmatrix} 2 & -4 & -2 \\ -7 & 2 & -1 \\ -3 & -6 & -5 \end{bmatrix} \xrightarrow{R_1/2} \begin{bmatrix} 1 & -2 & -1 \\ -7 & 2 & -1 \\ -3 & -6 & -5 \end{bmatrix}$$

Eliminate R_2 ($R_2 + 7R_1$) and R_3 ($R_3 + 3R_1$):

$$\begin{bmatrix} 1 & -2 & -1 \\ 0 & -12 & -8 \\ 0 & -12 & -8 \end{bmatrix} \xrightarrow{-R_2/4} \begin{bmatrix} 1 & -2 & -1 \\ 0 & 3 & 2 \\ 0 & 0 & 0 \end{bmatrix}$$

From R_2 : $3y + 2z = 0 \implies y = -\frac{2}{3}z$. Let $z = -3$, then $y = 2$. From R_1 : $x - 2y - z = 0 \implies x = 2(2) + (-3) = 1$.

$$\vec{v}_1 = \begin{bmatrix} 1 \\ 2 \\ -3 \end{bmatrix}$$

Case 2. $\lambda = -3$ Solve $(A + 3I)\vec{v} = \vec{0}$:

$$\begin{bmatrix} 1 & 2 & -1 \\ 2 & 4 & -2 \\ -3 & -6 & 3 \end{bmatrix} \xrightarrow{R_2-2R_1, R_3+3R_1} \begin{bmatrix} 1 & 2 & -1 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

Equation: $x + 2y - z = 0 \implies x = -2y + z$. Two free variables (y, z) .

1. Let $y = 1, z = 0 \implies x = -2$.

$$\implies \vec{v}_2 = \begin{bmatrix} -2 \\ 1 \\ 0 \end{bmatrix}$$

2. Let $y = 0, z = 1 \implies x = 1$.

$$\implies \vec{v}_3 = \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix}$$

Step 3. Construct P , D , and P^{-1}

$$P = \begin{bmatrix} 1 & -2 & 1 \\ 2 & 1 & 0 \\ -3 & 0 & 1 \end{bmatrix}, \quad D = \begin{bmatrix} 5 & 0 & 0 \\ 0 & -3 & 0 \\ 0 & 0 & -3 \end{bmatrix}$$

First, calculate $\det(P)$:

$$\det(P) = 1(1 - 0) - (-2)(2 - 0) + 1(0 - (-3)) = 1 + 4 + 3 = 8$$

Now, find the Cofactor Matrix C :

$$\begin{array}{lll} C_{11} = +(1) & C_{12} = -(2) & C_{13} = +(3) \\ C_{21} = -(-2) = 2 & C_{22} = +(1 - (-3)) = 4 & C_{23} = -(0 - 6) = 6 \\ C_{31} = +(-1) & C_{32} = -(0 - 2) = 2 & C_{33} = +(1 - (-4)) = 5 \end{array}$$

$$C = \begin{bmatrix} 1 & -2 & 3 \\ 2 & 4 & 6 \\ -1 & 2 & 5 \end{bmatrix} \implies \text{adj}(P) = C^T = \begin{bmatrix} 1 & 2 & -1 \\ -2 & 4 & 2 \\ 3 & 6 & 5 \end{bmatrix}$$

$$P^{-1} = \frac{1}{8} \begin{bmatrix} 1 & 2 & -1 \\ -2 & 4 & 2 \\ 3 & 6 & 5 \end{bmatrix}$$

Step 4. Compute A^5 We calculate A^5 using the formula $A^5 = PD^5P^{-1}$. First, compute the diagonal power matrix D^5 :

$$D^5 = \begin{bmatrix} 5^5 & 0 & 0 \\ 0 & (-3)^5 & 0 \\ 0 & 0 & (-3)^5 \end{bmatrix} = \begin{bmatrix} 3125 & 0 & 0 \\ 0 & -243 & 0 \\ 0 & 0 & -243 \end{bmatrix}$$

Next, we calculate:

$$\begin{aligned} PD^5P^{-1} &= \\ &= \frac{1}{8} \begin{bmatrix} 1 & -2 & 1 \\ 2 & 1 & 0 \\ -3 & 0 & 1 \end{bmatrix} \begin{bmatrix} 3125 & 0 & 0 \\ 0 & -243 & 0 \\ 0 & 0 & -243 \end{bmatrix} \begin{bmatrix} 1 & 2 & -1 \\ -2 & 4 & 2 \\ 3 & 6 & 5 \end{bmatrix} \\ &= \frac{1}{8} \begin{bmatrix} (3125) & ((-2)(-243)) & (-243) \\ ((2)(3125)) & (-243) & (0) \\ ((-3)(3125)) & (0) & (-243) \end{bmatrix} \begin{bmatrix} 1 & 2 & -1 \\ -2 & 4 & 2 \\ 3 & 6 & 5 \end{bmatrix} \\ &= \frac{1}{8} \begin{bmatrix} 3125 & 486 & -243 \\ 6250 & -243 & 0 \\ -9375 & 0 & -243 \end{bmatrix} \begin{bmatrix} 1 & 2 & -1 \\ -2 & 4 & 2 \\ 3 & 6 & 5 \end{bmatrix} \end{aligned}$$

Calculation of the final matrix:

$$\begin{aligned} c_{11} &= (3125)(1) + (486)(-2) + (-243)(3) = 3125 - 972 - 729 = 1424 \\ c_{12} &= (3125)(2) + (486)(4) + (-243)(6) = 6250 + 1944 - 1458 = 6736 \\ c_{13} &= (3125)(-1) + (486)(2) + (-243)(5) = -3125 + 972 - 1215 = -3368 \\ c_{21} &= (6250)(1) + (-243)(-2) + (0)(3) = 6250 + 486 + 0 = 6736 \\ c_{22} &= (6250)(2) + (-243)(4) + (0)(6) = 12500 - 972 + 0 = 11528 \\ c_{23} &= (6250)(-1) + (-243)(2) + (0)(5) = -6250 - 486 + 0 = -6736 \\ c_{31} &= (-9375)(1) + (0)(-2) + (-243)(3) = -9375 - 729 = -10104 \\ c_{32} &= (-9375)(2) + (0)(4) + (-243)(6) = -18750 - 1458 = -20208 \\ c_{33} &= (-9375)(-1) + (0)(2) + (-243)(5) = 9375 - 1215 = 8160 \end{aligned}$$

Substituting these values into the matrix, and dividing by 8 gives us the final matrix:

$$A^5 = \frac{1}{8} \begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{bmatrix} = \begin{bmatrix} 178 & 842 & -421 \\ 842 & 1441 & -842 \\ -1263 & -2526 & 1020 \end{bmatrix}$$

15 Question 14

Problem Use the properties of diagonalization of matrices to identify the given conic section:

$$16x^2 + 24xy + 9y^2 - 3x + 4y = 0$$

Solution The quadratic equation can be written in the matrix form

$$\vec{x}^T A \vec{x} + K \vec{x} = 0$$

where the matrix A represents the quadratic coefficients:

$$A = \begin{bmatrix} 16 & 12 \\ 12 & 9 \end{bmatrix}$$

Step 1. Find Eigenvalues of A We determine the type of conic section by inspecting the eigenvalues of A .

$$\det(A - \lambda I) = \begin{vmatrix} 16 - \lambda & 12 \\ 12 & 9 - \lambda \end{vmatrix} = 0$$

$$\begin{aligned} (16 - \lambda)(9 - \lambda) - (12)(12) &= 0 \\ (144 - 16\lambda - 9\lambda + \lambda^2) - 144 &= 0 \\ \lambda^2 - 25\lambda &= 0 \\ \lambda(\lambda - 25) &= 0 \end{aligned}$$

The eigenvalues are $\lambda_1 = 25$ and $\lambda_2 = 0$.

Conclusion Since one of the eigenvalues is zero ($\lambda_2 = 0$), the determinant of the quadratic form matrix is zero. This indicates that the conic section is a *Parabola*.

Step 2. Verification via Rotation To confirm the standard form, we diagonalize the quadratic part. The eigenvectors are found as follows:

For $\lambda_1 = 25$:

$$\begin{bmatrix} -9 & 12 \\ 12 & -16 \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} = \vec{0} \implies -3x + 4y = 0 \implies \vec{v}_1 = \begin{bmatrix} 4 \\ 3 \end{bmatrix}$$

Normalized: $\vec{u}_1 = \begin{bmatrix} 4/5 \\ 3/5 \end{bmatrix}$.

For $\lambda_2 = 0$:

$$\begin{bmatrix} 16 & 12 \\ 12 & 9 \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} = \vec{0} \implies 4x + 3y = 0 \implies \vec{v}_2 = \begin{bmatrix} -3 \\ 4 \end{bmatrix}$$

Normalized: $\vec{u}_2 = \begin{bmatrix} -3/5 \\ 4/5 \end{bmatrix}$.

The rotation matrix $P = \begin{bmatrix} 4/5 & -3/5 \\ 3/5 & 4/5 \end{bmatrix}$. Substituting coordinates $\begin{bmatrix} x \\ y \end{bmatrix} = P \begin{bmatrix} x' \\ y' \end{bmatrix}$ into the linear term $-3x + 4y$:

$$\begin{aligned} -3x + 4y &= [-3 \quad 4] P \begin{bmatrix} x' \\ y' \end{bmatrix} \\ &= [-3 \quad 4] \begin{bmatrix} 0.8 & -0.6 \\ 0.6 & 0.8 \end{bmatrix} \begin{bmatrix} x' \\ y' \end{bmatrix} \\ &= (-2.4 + 2.4)x' + (1.8 + 3.2)y' \\ &= 0x' + 5y' \end{aligned}$$

The rotated equation is:

$$25(x')^2 + 0(y')^2 + 5y' = 0 \implies 25(x')^2 = -5y' \implies (x')^2 = -\frac{1}{5}y'$$

This confirms the shape is a *Parabola*.

16 Question 15

Problem A quadratic form is given by

$$5x^2 - 2xy + 5y^2 = 24$$

Identify the conic section and illustrate the graph for the orthogonal form.

Solution The equation can be written in matrix form $\vec{x}^T A \vec{x} = 24$, where:

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

Step 1. Find Eigenvalues We solve the characteristic equation:

$$\begin{aligned} \det(A - \lambda I) &= \begin{vmatrix} 5 - \lambda & -1 \\ -1 & 5 - \lambda \end{vmatrix} = 0 \\ (5 - \lambda)^2 - (-1)(-1) &= 0 \\ (5 - \lambda)^2 - 1 &= 0 \\ (5 - \lambda)^2 = 1 &\implies 5 - \lambda = \pm 1 \end{aligned}$$

The eigenvalues are:

$$\lambda_1 = 5 - 1 = 4, \quad \lambda_2 = 5 + 1 = 6$$

Step 2. Identification Since both eigenvalues ($\lambda_1 = 4, \lambda_2 = 6$) are positive, the conic section is an *Ellipse*.

Step 3. Orthonormal Form The equation in the new coordinate system (x', y') defined by the eigenvectors is:

$$\lambda_1(x')^2 + \lambda_2(y')^2 = 24$$

$$4(x')^2 + 6(y')^2 = 24$$

Dividing by 24 to reach the standard form of an ellipse:

$$\frac{(x')^2}{6} + \frac{(y')^2}{4} = 1$$

Here, the semi-major axis is $a = \sqrt{6} \approx 2.45$ (along the x' axis) and the semi-minor axis is $b = 2$ (along the y' axis).

Step 4. Illustration To find the orientation of the axes, we find the eigenvector for $\lambda_1 = 4$:

$$(A - 4I)\vec{v} = \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} = \vec{0} \implies x - y = 0 \implies x = y$$

The principal axis x' is along the vector $(1, 1)$, which is a 45° rotation from the standard x -axis.

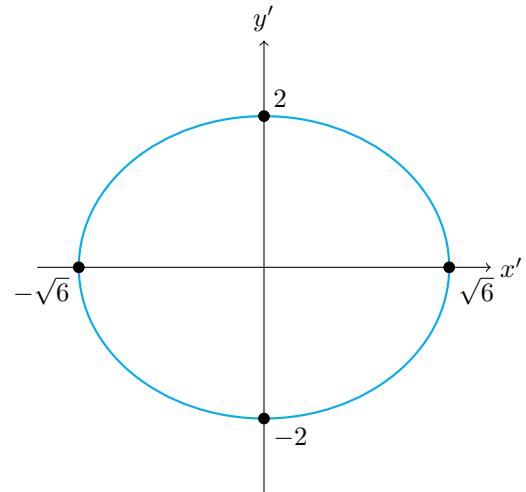


Figure: Graph of the orthonormal form $\frac{(x')^2}{6} + \frac{(y')^2}{4} = 1$

17 Question 16

Problem Determine whether the given matrix A is diagonalizable. If so, find the matrix P that diagonalizes A and the diagonal matrix D such that $D = P^{-1}AP$.

$$A = \begin{bmatrix} 1 & 2 \\ -\frac{1}{2} & 1 \end{bmatrix}$$

Solution Step 1. Find Eigenvalues We find the eigenvalues by solving the characteristic equation $\det(A - \lambda I) = 0$:

$$\begin{aligned} \begin{vmatrix} 1-\lambda & 2 \\ -1/2 & 1-\lambda \end{vmatrix} &= 0 \\ (1-\lambda)(1-\lambda) - (2)\left(-\frac{1}{2}\right) &= 0 \\ (1-\lambda)^2 - (-1) &= 0 \\ (1-\lambda)^2 + 1 &= 0 \end{aligned}$$

Solving for λ :

$$\begin{aligned} (1-\lambda)^2 &= -1 \\ 1-\lambda &= \pm\sqrt{-1} \\ 1-\lambda &= \pm i \\ \lambda &= 1 \pm i \end{aligned}$$

The eigenvalues are $\lambda_1 = 1 + i$ and $\lambda_2 = 1 - i$.

Conclusion Since the eigenvalues are complex (not real numbers), there are no corresponding eigenvectors with real components. Therefore, the matrix A is *not diagonalizable* over the field of real numbers \mathbb{R} .

18 Question 17

Problem If $\rho(x, y)$ is the density of a wire (mass per unit length), then $m = \int_C \rho(x, y)ds$ is the mass of the wire.

- i) Find the mass of a wire having the shape of the semicircle $x = 1 + \cos t$, $y = \sin t$, $0 \leq t \leq \pi$, if the density at a point P is directly proportional to its distance from the y-axis.
- ii) Find the coordinates of the center of mass (\bar{x}, \bar{y}) .

Solution

- i) **Find the Mass** The mass is given by the line integral $m = \int_C \rho(x, y)ds$.

1. Parameterization:

$$\vec{r}(t) = (1 + \cos t)\hat{i} + (\sin t)\hat{j}, \quad 0 \leq t \leq \pi$$

2. Differential Element ds :

Calculate the derivatives:

$$\frac{dx}{dt} = -\sin t, \quad \frac{dy}{dt} = \cos t$$

Calculate the magnitude:

$$ds = \sqrt{(-\sin t)^2 + (\cos t)^2} dt = \sqrt{\sin^2 t + \cos^2 t} dt = 1 dt$$

3. Density Function:

The density is proportional to the distance from the y-axis ($|x|$). Since $x = 1 + \cos t \geq 0$ for the given domain:

$$\rho(x, y) = kx = k(1 + \cos t)$$

where k is a constant of proportionality.

4. Integral for Mass:

$$\begin{aligned} m &= \int_0^\pi k(1 + \cos t)(1) dt \\ &= k [t + \sin t]_0^\pi \\ &= k[(\pi + 0) - (0 + 0)] \\ &= k\pi \end{aligned}$$

ii) Find Center of Mass The coordinates are given by $\bar{x} = M_y/m$ and $\bar{y} = M_x/m$.

Calculate M_y (Moment about y-axis):

$$M_y = \int_C x\rho(x,y)ds = \int_0^\pi (1 + \cos t)k(1 + \cos t)dt$$

$$M_y = k \int_0^\pi (1 + \cos t)^2 dt = k \int_0^\pi (1 + 2\cos t + \cos^2 t)dt$$

Using the identity $\cos^2 t = (1 + \cos 2t)/2$:

$$\begin{aligned} M_y &= k \int_0^\pi \left(1 + 2\cos t + \frac{1}{2} + \frac{1}{2}\cos 2t\right) dt \\ &= k \int_0^\pi \left(\frac{3}{2} + 2\cos t + \frac{1}{2}\cos 2t\right) dt \\ &= k \left[\frac{3}{2}t + 2\sin t + \frac{1}{4}\sin 2t\right]_0^\pi \\ &= k \left[\left(\frac{3\pi}{2} + 0 + 0\right) - 0\right] = \frac{3\pi k}{2} \\ \bar{x} &= \frac{M_y}{m} = \frac{3\pi k/2}{k\pi} = \frac{3}{2} \end{aligned}$$

Calculate M_x (Moment about x-axis):

$$M_x = \int_C y\rho(x,y)ds = \int_0^\pi (\sin t)k(1 + \cos t)dt$$

$$M_x = k \int_0^\pi (\sin t + \sin t \cos t)dt$$

Using simple integration for $\sin t$ and u -substitution (or identity $\sin 2t$) for $\sin t \cos t$:

$$\begin{aligned} M_x &= k \left[-\cos t + \frac{1}{2}\sin^2 t\right]_0^\pi \\ &= k [(-\cos \pi + 0) - (-\cos 0 + 0)] \\ &= k [(-1) - (-1)] = k(1 + 1) = 2k \end{aligned}$$

$$\bar{y} = \frac{M_x}{m} = \frac{2k}{k\pi} = \frac{2}{\pi}$$

Answer: The mass is $m = k\pi$, and the center of mass is located at $(3/2, 2/\pi)$.

19 Question 18

Problem If $u = f(x, y)$ and $x = r \cos \theta, y = r \sin \theta$, show that Laplace's Equation

$$\frac{\partial^2 u}{\partial r^2} + \frac{1}{r} \frac{\partial u}{\partial r} + \frac{1}{r^2} \frac{\partial^2 u}{\partial \theta^2} = 0$$

Solution We perform the change of variables using the Chain Rule. Given:

$$x = r \cos \theta, \quad y = r \sin \theta \implies r = \sqrt{x^2 + y^2}, \quad \theta = \arctan\left(\frac{y}{x}\right)$$

Step 1. First Partial Derivatives of Coordinates We calculate the derivatives of r and θ with respect to x and y :

$$\begin{aligned} \frac{\partial r}{\partial x} &= \frac{x}{\sqrt{x^2 + y^2}} = \frac{r \cos \theta}{r} = \cos \theta & \frac{\partial r}{\partial y} &= \sin \theta \\ \frac{\partial \theta}{\partial x} &= \frac{1}{1 + (y/x)^2} \left(-\frac{y}{x^2}\right) = -\frac{y}{r^2} = -\frac{\sin \theta}{r} & \frac{\partial \theta}{\partial y} &= \frac{\cos \theta}{r} \end{aligned}$$

Step 2. First Partial Derivative of u Using the chain rule: $\frac{\partial u}{\partial x} = \frac{\partial u}{\partial r} \frac{\partial r}{\partial x} + \frac{\partial u}{\partial \theta} \frac{\partial \theta}{\partial x}$:

$$u_x = (\cos \theta)u_r - \left(\frac{\sin \theta}{r}\right)u_\theta \tag{5}$$

Similarly for y :

$$u_y = (\sin \theta)u_r + \left(\frac{\cos \theta}{r}\right)u_\theta \tag{6}$$

Step 3. Second Partial Derivative u_{xx} We apply the operator $\frac{\partial}{\partial x} = \cos \theta \frac{\partial}{\partial r} - \frac{\sin \theta}{r} \frac{\partial}{\partial \theta}$ to equation (5). (Note: We must use the product rule because the coefficients depend on r and θ)

$$\begin{aligned} u_{xx} &= \frac{\partial}{\partial x} \left(\cos \theta \cdot u_r - \frac{\sin \theta}{r} \cdot u_\theta \right) \\ &= \cos \theta \frac{\partial}{\partial x} (u_r) + u_r \frac{\partial}{\partial x} (\cos \theta) - \left[\frac{\sin \theta}{r} \frac{\partial}{\partial x} (u_\theta) + u_\theta \frac{\partial}{\partial x} \left(\frac{\sin \theta}{r} \right) \right] \end{aligned}$$

Expanding terms individually is tedious. A cleaner way is to apply the full operator to the full expression:

$$\begin{aligned} u_{xx} &= \left(\cos \theta \partial_r - \frac{\sin \theta}{r} \partial_\theta \right) \left(\cos \theta u_r - \frac{\sin \theta}{r} u_\theta \right) \\ &= \cos^2 \theta u_{rr} - \frac{2 \sin \theta \cos \theta}{r} u_{r\theta} + \frac{\sin^2 \theta}{r^2} u_{\theta\theta} + \frac{\sin^2 \theta}{r} u_r + \frac{2 \sin \theta \cos \theta}{r^2} u_\theta \end{aligned}$$

Step 4. Second Partial Derivative u_{yy} We apply $\frac{\partial}{\partial y} = \sin \theta \frac{\partial}{\partial r} + \frac{\cos \theta}{r} \frac{\partial}{\partial \theta}$ to equation (6):

$$\begin{aligned} u_{yy} &= \left(\sin \theta \partial_r + \frac{\cos \theta}{r} \partial_\theta \right) \left(\sin \theta u_r + \frac{\cos \theta}{r} u_\theta \right) \\ &= \sin^2 \theta u_{rr} + \frac{2 \sin \theta \cos \theta}{r} u_{r\theta} + \frac{\cos^2 \theta}{r^2} u_{\theta\theta} + \frac{\cos^2 \theta}{r} u_r - \frac{2 \sin \theta \cos \theta}{r^2} u_\theta \end{aligned}$$

Step 5. Summation $u_{xx} + u_{yy}$ Adding the two expanded expressions:

$$\begin{aligned} u_{xx} + u_{yy} &= (\cos^2 \theta + \sin^2 \theta) u_{rr} \\ &\quad + \frac{1}{r} (\sin^2 \theta + \cos^2 \theta) u_r \\ &\quad + \frac{1}{r^2} (\sin^2 \theta + \cos^2 \theta) u_{\theta\theta} \\ &\quad + (\text{Terms with } u_{r\theta} \text{ and } u_\theta \text{ cancel out}) \end{aligned}$$

Since $\cos^2 \theta + \sin^2 \theta = 1$, we arrive at the final form:

$$\nabla^2 u = u_{rr} + \frac{1}{r} u_r + \frac{1}{r^2} u_{\theta\theta} = 0$$

This completes the derivation.

20 Question 19

Problem The temperature T at a point (x, y, z) is inversely proportional to the square of the distance from the origin. Given $T(0, 0, 1) = 500$:

1. Find the rate of change of T at $(2, 3, 3)$ in the direction of $(3, 1, 1)$.
2. In which direction does T increase most rapidly?
3. What is the maximum rate of change?

Solution

Step 1. Define the Temperature Function Let r be the distance from the origin, $r^2 = x^2 + y^2 + z^2$. The problem states $T = \frac{k}{r^2} = \frac{k}{x^2+y^2+z^2}$. Using the condition $T(0, 0, 1) = 500$:

$$500 = \frac{k}{0^2 + 0^2 + 1^2} \implies k = 500$$

So, $T(x, y, z) = 500(x^2 + y^2 + z^2)^{-1}$.

Step 2. Calculate the Gradient ∇T We compute the partial derivatives:

$$\begin{aligned}\frac{\partial T}{\partial x} &= -500(x^2 + y^2 + z^2)^{-2}(2x) = -\frac{1000x}{(x^2 + y^2 + z^2)^2} \\ \frac{\partial T}{\partial y} &= -\frac{1000y}{(x^2 + y^2 + z^2)^2} \\ \frac{\partial T}{\partial z} &= -\frac{1000z}{(x^2 + y^2 + z^2)^2}\end{aligned}$$

$$\nabla T = -\frac{1000}{(x^2 + y^2 + z^2)^2} \langle x, y, z \rangle$$

Step 3. Evaluate Gradient at $P(2, 3, 3)$ First, calculate the squared distance at P :

$$r^2 = 2^2 + 3^2 + 3^2 = 4 + 9 + 9 = 22$$

Now substitute into the gradient expression:

$$\begin{aligned}\nabla T(2, 3, 3) &= -\frac{1000}{(22)^2} \langle 2, 3, 3 \rangle = -\frac{1000}{484} \langle 2, 3, 3 \rangle = -\frac{250}{121} \langle 2, 3, 3 \rangle \\ \nabla T &= \left\langle -\frac{500}{121}, -\frac{750}{121}, -\frac{750}{121} \right\rangle\end{aligned}$$

Part 1. Rate of Change in Direction $\vec{v} = (3, 1, 1)$ We need the unit vector \vec{u} in the direction of \vec{v} :

$$|\vec{v}| = \sqrt{3^2 + 1^2 + 1^2} = \sqrt{9 + 1 + 1} = \sqrt{11}$$

$$\vec{u} = \frac{1}{\sqrt{11}} \langle 3, 1, 1 \rangle$$

The directional derivative is $D_{\vec{u}}T = \nabla T \cdot \vec{u}$:

$$\begin{aligned} D_{\vec{u}}T &= \left(-\frac{250}{121} \langle 2, 3, 3 \rangle \right) \cdot \left(\frac{1}{\sqrt{11}} \langle 3, 1, 1 \rangle \right) \\ &= -\frac{250}{121\sqrt{11}} ((2)(3) + (3)(1) + (3)(1)) \\ &= -\frac{250}{121\sqrt{11}} (6 + 3 + 3) = -\frac{250(12)}{121\sqrt{11}} \\ &= -\frac{3000}{121\sqrt{11}} \approx -7.47 \end{aligned}$$

Part 2. Direction of Most Rapid Increase Temperature increases most rapidly in the direction of the gradient vector ∇T .

$$\text{Direction} = \nabla T = -\frac{250}{121} \langle 2, 3, 3 \rangle$$

Since the scalar is negative, this vector points towards the origin (opposite to the position vector). Normalized direction: $\vec{u}_{max} = \frac{\langle -2, -3, -3 \rangle}{\sqrt{22}}$.

Part 3. Maximum Rate of Change The maximum rate is the magnitude of the gradient vector $|\nabla T|$:

$$\begin{aligned} |\nabla T| &= \left| -\frac{250}{121} \langle 2, 3, 3 \rangle \right| \\ &= \frac{250}{121} \sqrt{2^2 + 3^2 + 3^2} \\ &= \frac{250}{121} \sqrt{22} \approx 9.69 \end{aligned}$$

21 Question 20

Problem: Any scalar function f for which $\nabla^2 f = 0$ (Laplace's Equation) is said to be harmonic. Verify that $f(x, y, z) = (x^2 + y^2 + z^2)^{-1/2}$ is harmonic except at the origin.

Solution Let $r = \sqrt{x^2 + y^2 + z^2}$. The function can be written as $f = r^{-1} = (x^2 + y^2 + z^2)^{-1/2}$. We need to show that $\nabla^2 f = \frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2} + \frac{\partial^2 f}{\partial z^2} = 0$.

Step 1. Partial Derivatives with respect to x First derivative:

$$\begin{aligned}\frac{\partial f}{\partial x} &= -\frac{1}{2}(x^2 + y^2 + z^2)^{-3/2} \cdot (2x) \\ &= -x(x^2 + y^2 + z^2)^{-3/2}\end{aligned}$$

Second derivative (using Product Rule):

$$\begin{aligned}\frac{\partial^2 f}{\partial x^2} &= \frac{\partial}{\partial x} \left[-x(x^2 + y^2 + z^2)^{-3/2} \right] \\ &= (-1)(x^2 + y^2 + z^2)^{-3/2} + (-x) \left[-\frac{3}{2}(x^2 + y^2 + z^2)^{-5/2} \cdot (2x) \right] \\ &= -(x^2 + y^2 + z^2)^{-3/2} + 3x^2(x^2 + y^2 + z^2)^{-5/2}\end{aligned}$$

To combine terms, multiply the first term by $\frac{x^2 + y^2 + z^2}{x^2 + y^2 + z^2}$:

$$\frac{\partial^2 f}{\partial x^2} = \frac{-(x^2 + y^2 + z^2) + 3x^2}{(x^2 + y^2 + z^2)^{5/2}} = \frac{2x^2 - y^2 - z^2}{(x^2 + y^2 + z^2)^{5/2}}$$

Step 2. Partial Derivatives with respect to y and z By symmetry, the derivatives for y and z follow the exact same pattern:

$$\begin{aligned}\frac{\partial^2 f}{\partial y^2} &= \frac{2y^2 - x^2 - z^2}{(x^2 + y^2 + z^2)^{5/2}} \\ \frac{\partial^2 f}{\partial z^2} &= \frac{2z^2 - x^2 - y^2}{(x^2 + y^2 + z^2)^{5/2}}\end{aligned}$$

Step 3. Summation Summing the numerators:

$$\begin{aligned}\text{Numerator} &= (2x^2 - y^2 - z^2) + (2y^2 - x^2 - z^2) + (2z^2 - x^2 - y^2) \\ &= (2x^2 - x^2 - x^2) + (2y^2 - y^2 - y^2) + (2z^2 - z^2 - z^2) \\ &= 0 + 0 + 0 = 0\end{aligned}$$

Thus:

$$\nabla^2 f = \frac{0}{(x^2 + y^2 + z^2)^{5/2}} = 0$$

Since the Laplacian is zero for all points where $x^2 + y^2 + z^2 \neq 0$, the function is harmonic everywhere except at the origin.

22 Question 21

Problem Evaluate $\oint_C \vec{f} \cdot d\vec{r}$ for the path $C = C_1 + C_2 + C_3 + C_4$ shown in the figure, where $\vec{f}(x, y, z) = (y - x^2)\hat{i} + (x - y^2z)\hat{j} - yz^2\hat{k}$. The vertices are $A(2, 1, 0)$, $B(0, 1, 0)$, $C(0, 1, 2)$, and $D(2, 0, 0)$.

Solution

1. Segment C_1 : From $D(2, 0, 0)$ to $B(0, 1, 0)$

Parameterization: x goes from 2 to 0, y goes from 0 to 1, $z = 0$. Let $x = 2 - 2t$, $y = t$, $z = 0$ for $t \in [0, 1]$.

Differentials: $dx = -2dt$, $dy = dt$, $dz = 0$. Substitute into the integral:

$$\begin{aligned} I_1 &= \int_0^1 [(t - (2 - 2t)^2)(-2) + ((2 - 2t) - t^2(0))(1) + 0] dt \\ &= \int_0^1 [-2(t - (4 - 8t + 4t^2)) + 2 - 2t] dt \\ &= \int_0^1 [-2t + 8 - 16t + 8t^2 + 2 - 2t] dt \\ &= \int_0^1 [8t^2 - 20t + 10] dt \\ &= \left[\frac{8}{3}t^3 - 10t^2 + 10t \right]_0^1 = \frac{8}{3} - 10 + 10 = \frac{8}{3} \end{aligned}$$

2. Segment C_2 : From $B(0, 1, 0)$ to $C(0, 1, 2)$

Parameterization: $x = 0$, $y = 1$, $z = t$ for $t \in [0, 2]$.

Differentials: $dx = 0$, $dy = 0$, $dz = dt$.

$$\begin{aligned} I_2 &= \int_0^2 [-yz^2] dt = \int_0^2 -(1)(t^2) dt \\ &= \left[-\frac{t^3}{3} \right]_0^2 = -\frac{8}{3} \end{aligned}$$

3. Segment C_3 : From $C(0, 1, 2)$ to $A(2, 1, 0)$

Parameterization: $x = 2t$, $y = 1$, $z = 2 - 2t$ for $t \in [0, 1]$.

Differentials: $dx = 2dt, dy = 0, dz = -2dt$.

$$\begin{aligned}
I_3 &= \int_0^1 [(1 - (2t)^2)(2) + 0 - (1)(2 - 2t)^2(-2)] dt \\
&= \int_0^1 [2(1 - 4t^2) + 2(2 - 2t)^2] dt \\
&= \int_0^1 [2 - 8t^2 + 2(4 - 8t + 4t^2)] dt \\
&= \int_0^1 [2 - 8t^2 + 8 - 16t + 8t^2] dt \\
&= \int_0^1 (10 - 16t) dt \\
&= [10t - 8t^2]_0^1 = 10 - 8 = 2
\end{aligned}$$

4. Segment C_4 : From $A(2, 1, 0)$ to $D(2, 0, 0)$

Parameterization: $x = 2, z = 0, y$ goes from 1 to 0. Let $y = t$ from 1 to 0.
Differentials: $dx = 0, dz = 0, dy = dt$.

$$\begin{aligned}
I_4 &= \int_1^0 [(x - y^2 z)] dy = \int_1^0 (2 - y^2(0)) dy \\
&= \int_1^0 2 dy = [2y]_1^0 = 0 - 2 = -2
\end{aligned}$$

Total Integral

$$\oint_C \vec{f} \cdot d\vec{r} = I_1 + I_2 + I_3 + I_4 = \frac{8}{3} - \frac{8}{3} + 2 - 2 = 0$$

Final Answer The value of the line integral is 0.

23 Question 22

Problem If $\vec{f} = (2xy - x^2)\hat{i} + (x + y^2)\hat{j}$, verify Green's Theorem in the plane where S is the closed region bounded by $y = x^2$ and $x = y^2$. The path $C = C_1 + C_2$ is shown in the figure.

Solution Green's Theorem states:

$$\oint_C \vec{f} \cdot d\vec{r} = \iint_S \left(\frac{\partial M}{\partial x} - \frac{\partial L}{\partial y} \right) dA$$

where $\vec{f} = L\hat{i} + M\hat{j}$.

Given: $L = 2xy - x^2$ and $M = x + y^2$.

Part 1. The Double Integral We compute the partial derivatives:

$$\frac{\partial M}{\partial x} = 1, \quad \frac{\partial L}{\partial y} = 2x$$

$$\text{Integrand} = \frac{\partial M}{\partial x} - \frac{\partial L}{\partial y} = 1 - 2x$$

The region S is bounded by $y = x^2$ (lower curve) and $y = \sqrt{x}$ (upper curve) from $x = 0$ to $x = 1$.

$$\begin{aligned} \iint_S (1 - 2x) dy dx &= \int_0^1 \int_{x^2}^{\sqrt{x}} (1 - 2x) dy dx \\ &= \int_0^1 (1 - 2x)[y]_{x^2}^{\sqrt{x}} dx \\ &= \int_0^1 (1 - 2x)(\sqrt{x} - x^2) dx \\ &= \int_0^1 (x^{1/2} - x^2 - 2x^{3/2} + 2x^3) dx \\ &= \left[\frac{2}{3}x^{3/2} - \frac{x^3}{3} - 2\left(\frac{2}{5}x^{5/2}\right) + \frac{2x^4}{4} \right]_0^1 \\ &= \left(\frac{2}{3} - \frac{1}{3} - \frac{4}{5} + \frac{1}{2} \right) - 0 \\ &= \frac{1}{3} - \frac{4}{5} + \frac{1}{2} \\ &= \frac{10}{30} - \frac{24}{30} + \frac{15}{30} \\ &= \frac{1}{30} \end{aligned}$$

Part 2. The Line Integral The line integral is $\oint_C (2xy - x^2)dx + (x + y^2)dy$.

Segment C_1 : Along $y = x^2$ from $(0,0)$ to $(1,1)$ Let $x = t, y = t^2$ for $t \in [0, 1]$. Then $dx = dt, dy = 2tdt$.

$$\begin{aligned} I_1 &= \int_0^1 [(2(t)(t^2) - t^2)(1) + (t + (t^2)^2)(2t)] dt \\ &= \int_0^1 [(2t^3 - t^2) + (2t^2 + 2t^5)] dt \\ &= \int_0^1 (2t^5 + 2t^3 + t^2) dt \\ &= \left[\frac{2t^6}{6} + \frac{2t^4}{4} + \frac{t^3}{3} \right]_0^1 \\ &= \frac{1}{3} + \frac{1}{2} + \frac{1}{3} = \frac{2}{3} + \frac{1}{2} = \frac{7}{6} \end{aligned}$$

Segment C_2 : Along $x = y^2$ from $(1,1)$ to $(0,0)$ Let $y = t$ from $t = 1$ to 0 . Then $x = t^2, dx = 2tdt$.

$$\begin{aligned} I_2 &= \int_1^0 [(2(t^2)(t) - (t^2)^2)(2t) + (t^2 + t^2)(1)] dt \\ &= \int_1^0 [(2t^3 - t^4)(2t) + 2t^2] dt \\ &= \int_1^0 (4t^4 - 2t^5 + 2t^2) dt \\ &= \left[\frac{4t^5}{5} - \frac{2t^6}{6} + \frac{2t^3}{3} \right]_1^0 \\ &= 0 - \left(\frac{4}{5} - \frac{1}{3} + \frac{2}{3} \right) \\ &= -\left(\frac{4}{5} + \frac{1}{3} \right) = -\left(\frac{12}{15} + \frac{5}{15} \right) = -\frac{17}{15} \end{aligned}$$

Total Line Integral:

$$\oint_C \vec{f} \cdot d\vec{r} = I_1 + I_2 = \frac{7}{6} - \frac{17}{15}$$

Find common denominator (30):

$$\frac{35}{30} - \frac{34}{30} = \frac{1}{30}$$

Conclusion: Since the double integral $(\frac{1}{30})$ equals the line integral $(\frac{1}{30})$, Green's Theorem is verified.

24 Question 23

Problem Verify Stokes' Theorem $\iint_S (\nabla \times \vec{f}) \cdot d\vec{s} = \oint_C \vec{f} \cdot d\vec{r}$ for the vector field $\vec{f} = xz^2\hat{i} - yx\hat{j} + zy^2\hat{k}$, where S is the upper hemisphere $x^2 + y^2 + z^2 = 9$ ($0 \leq z \leq 3$) and C is its circular boundary on the xy -plane.

Solution

Part 1. The Line Integral The boundary C is the circle $x^2 + y^2 = 9$ on the plane $z = 0$. Since $z = 0$ everywhere on C , we have $dz = 0$. Substituting $z = 0$ into the vector field \vec{f} :

$$\vec{f}(x, y, 0) = x(0)^2\hat{i} - yx\hat{j} + (0)y^2\hat{k} = -yx\hat{j}$$

The line integral simplifies to:

$$\oint_C \vec{f} \cdot d\vec{r} = \oint_C (0dx - yxdy + 0dz) = \oint_C -xy dy$$

We parameterize the circle C (counter-clockwise, radius 3):

$$x = 3 \cos t, \quad y = 3 \sin t, \quad dy = 3 \cos t dt, \quad t \in [0, 2\pi]$$

Substitute into the integral:

$$\begin{aligned} I &= \int_0^{2\pi} -(3 \cos t)(3 \sin t)(3 \cos t) dt \\ &= -27 \int_0^{2\pi} \cos^2 t \sin t dt \end{aligned}$$

Let $u = \cos t$, then $du = -\sin t dt$. Limits: $t = 0 \implies u = 1$, $t = 2\pi \implies u = 1$.

$$I = -27 \int_1^1 u^2(-du) = 0$$

Result: The line integral is **0**.

Part 2. The Surface Integral First, we compute the Curl of \vec{f} :

$$\nabla \times \vec{f} = \begin{vmatrix} \hat{i} & \hat{j} & \hat{k} \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ xz^2 & -yx & zy^2 \end{vmatrix}$$

$$\hat{i}\text{-component: } \frac{\partial}{\partial y}(zy^2) - \frac{\partial}{\partial z}(-yx) = 2zy - 0 = 2yz$$

$$\hat{j}\text{-component: } -\left(\frac{\partial}{\partial x}(zy^2) - \frac{\partial}{\partial z}(xz^2)\right) = -(0 - 2xz) = 2xz$$

$$\hat{k}\text{-component: } \frac{\partial}{\partial x}(-yx) - \frac{\partial}{\partial y}(xz^2) = -y - 0 = -y$$

$$\nabla \times \vec{f} = \langle 2yz, 2xz, -y \rangle$$

The outward unit normal for the sphere $x^2 + y^2 + z^2 = 9$ is $\hat{n} = \frac{1}{3}\langle x, y, z \rangle$. We calculate the dot product $(\nabla \times \vec{f}) \cdot \hat{n}$:

$$\begin{aligned} (\nabla \times \vec{f}) \cdot \hat{n} &= \frac{1}{3} [(2yz)(x) + (2xz)(y) + (-y)(z)] \\ &= \frac{1}{3}[2xyz + 2xyz - yz] \\ &= \frac{1}{3}[4xyz - yz] \end{aligned}$$

We now integrate this scalar field over the hemisphere using spherical coordinates:

$$x = 3 \sin \phi \cos \theta, \quad y = 3 \sin \phi \sin \theta, \quad z = 3 \cos \phi$$

The area element is $dS = 9 \sin \phi d\phi d\theta$. The integral splits into two terms:

$$I_S = \iint_S \frac{4}{3}xyz \, dS - \iint_S \frac{1}{3}yz \, dS$$

Term 1 analysis ($4xyz$): The term involves the product $xy \propto \cos \theta \sin \theta = \frac{1}{2} \sin(2\theta)$. Integration with respect to θ from 0 to 2π :

$$\int_0^{2\pi} \sin(2\theta) \, d\theta = 0 \implies \text{The first term vanishes.}$$

Term 2 analysis ($-yz$): The term involves $y \propto \sin \theta$. Integration with respect to θ from 0 to 2π :

$$\int_0^{2\pi} \sin \theta \, d\theta = 0 \implies \text{The second term vanishes.}$$

Conclusion

Since both terms integrate to zero due to symmetry:

$$\iint_S (\nabla \times \vec{f}) \cdot d\vec{s} = 0$$

Both the line integral and surface integral yield 0, verifying Stokes' Theorem.

25 Question 24

Problem Verify Stokes' Theorem $\iint_S (\nabla \times \vec{f}) \cdot d\vec{s} = \oint_C \vec{f} \cdot d\vec{r}$ for the vector field $\vec{f} = y\hat{i} + z\hat{j} + x\hat{k}$. The surface S is the paraboloid $z = 1 - (x^2 + y^2)$ for $z \geq 0$, bounded by the circle C in the xy -plane.

Solution

Part 1. The Line Integral The boundary curve C is the circle $x^2 + y^2 = 1$ lying in the plane $z = 0$. Orientation is counter-clockwise (standard positive orientation).

Parameterization: Let $x = \cos t$, $y = \sin t$, $z = 0$ for $t \in [0, 2\pi]$. The differential vector $d\vec{r}$ is:

$$d\vec{r} = \langle -\sin t, \cos t, 0 \rangle dt$$

Substitute the coordinates into the vector field $\vec{f} = \langle y, z, x \rangle$:

$$\vec{f}(t) = \langle \sin t, 0, \cos t \rangle$$

(Note: $y = \sin t$, $z = 0$, $x = \cos t$)

Calculate Dot Product:

$$\begin{aligned} \vec{f} \cdot d\vec{r} &= \langle \sin t, 0, \cos t \rangle \cdot \langle -\sin t, \cos t, 0 \rangle \\ &= (\sin t)(-\sin t) + (0)(\cos t) + (\cos t)(0) \\ &= -\sin^2 t \end{aligned}$$

Evaluate Integral:

$$\begin{aligned} \oint_C \vec{f} \cdot d\vec{r} &= \int_0^{2\pi} -\sin^2 t dt \\ &= - \int_0^{2\pi} \frac{1 - \cos(2t)}{2} dt \\ &= -\frac{1}{2} \left[t - \frac{\sin(2t)}{2} \right]_0^{2\pi} \\ &= -\frac{1}{2} [(2\pi - 0) - (0 - 0)] \\ &= -\pi \end{aligned}$$

Part 2. The Surface Integral First, calculate the Curl of $\vec{f} = \langle y, z, x \rangle$:

$$\nabla \times \vec{f} = \begin{vmatrix} \hat{i} & \hat{j} & \hat{k} \\ \partial_x & \partial_y & \partial_z \\ y & z & x \end{vmatrix}$$

$$\hat{i}\text{-component: } \frac{\partial}{\partial y}(x) - \frac{\partial}{\partial z}(z) = 0 - 1 = -1$$

$$\hat{j}\text{-component: } \frac{\partial}{\partial z}(y) - \frac{\partial}{\partial x}(x) = 0 - 1 = -1$$

$$\hat{k}\text{-component: } \frac{\partial}{\partial x}(z) - \frac{\partial}{\partial y}(y) = 0 - 1 = -1$$

$$\nabla \times \vec{f} = \langle -1, -1, -1 \rangle$$

Surface Parameterization: The surface is given explicitly by $z = g(x, y) = 1 - x^2 - y^2$. For a graph $z = g(x, y)$ with upward orientation, the normal vector $d\vec{s}$ is given by:

$$d\vec{s} = \langle -g_x, -g_y, 1 \rangle dA$$

Calculating partial derivatives of z :

$$g_x = -2x \implies -g_x = 2x$$

$$g_y = -2y \implies -g_y = 2y$$

$$d\vec{s} = \langle 2x, 2y, 1 \rangle dA$$

Calculate Flux Integrand:

$$(\nabla \times \vec{f}) \cdot d\vec{s} = \langle -1, -1, -1 \rangle \cdot \langle 2x, 2y, 1 \rangle = -2x - 2y - 1$$

Evaluate Surface Integral: The domain D is the projection of the paraboloid onto the xy -plane, which is the unit disk $x^2 + y^2 \leq 1$. Using polar coordinates: $x = r \cos \theta, y = r \sin \theta, dA = r dr d\theta$.

$$\begin{aligned} \iint_S (\nabla \times \vec{f}) \cdot d\vec{s} &= \iint_D (-2x - 2y - 1) dA \\ &= \int_0^{2\pi} \int_0^1 (-2r \cos \theta - 2r \sin \theta - 1) r dr d\theta \\ &= \int_0^{2\pi} \int_0^1 (-2r^2 \cos \theta - 2r^2 \sin \theta - r) dr d\theta \end{aligned}$$

We can split this into three terms.

1. $\int_0^{2\pi} \cos \theta d\theta = 0 \implies$ The x term vanishes.
2. $\int_0^{2\pi} \sin \theta d\theta = 0 \implies$ The y term vanishes.
3. The remaining term is the constant -1 :

$$\begin{aligned} I &= \int_0^{2\pi} d\theta \int_0^1 -r dr \\ &= (2\pi) \left[-\frac{r^2}{2} \right]_0^1 \\ &= 2\pi \left(-\frac{1}{2} \right) = -\pi \end{aligned}$$

Conclusion

Since $\oint_C \vec{f} \cdot d\vec{r} = -\pi$ and $\iint_S (\nabla \times \vec{f}) \cdot d\vec{s} = -\pi$, Stokes' Theorem is verified.

26 Question 25

Problem Verify the Divergence Theorem of Gauss $\iiint_V (\nabla \cdot \vec{f}) dV = \iint_S \vec{f} \cdot d\vec{s}$ for the vector field $\vec{f} = 2x^2y\hat{i} - y^2\hat{j} + 4xz^2\hat{k}$. The volume V is bounded by $x = 0, x = 2, y = 0, z = 0$ and the cylinder $y^2 + z^2 = 9$.

Solution

Part 1. The Volume Integral First, calculate the divergence of \vec{f} :

$$\begin{aligned}\nabla \cdot \vec{f} &= \frac{\partial}{\partial x}(2x^2y) + \frac{\partial}{\partial y}(-y^2) + \frac{\partial}{\partial z}(4xz^2) \\ &= 4xy - 2y + 8xz\end{aligned}$$

We integrate this over the volume V . The region is a quarter-cylinder along the x -axis. It is best described using polar coordinates for y and z :

$$y = r \cos \theta, \quad z = r \sin \theta, \quad x = x$$

Limits: $0 \leq x \leq 2$, $0 \leq r \leq 3$, $0 \leq \theta \leq \pi/2$ (First quadrant).

The volume element is $dV = r dr d\theta dx$.

Substituting variables into the divergence:

$$\nabla \cdot \vec{f} = 4x(r \cos \theta) - 2(r \cos \theta) + 8x(r \sin \theta)$$

The integral is:

$$I_V = \int_0^{\pi/2} \int_0^3 \int_0^2 (4xr \cos \theta - 2r \cos \theta + 8xr \sin \theta) r dx dr d\theta$$

Integrating with respect to x first (0 to 2):

$$\begin{aligned}\int_0^2 (\dots) dx &= [2x^2r \cos \theta - 2xr \cos \theta + 4x^2r \sin \theta]_0^2 \\ &= (8r \cos \theta - 4r \cos \theta + 16r \sin \theta) - 0 \\ &= 4r \cos \theta + 16r \sin \theta\end{aligned}$$

Now integrate with respect to r (0 to 3), remembering the extra r from dV :

$$\begin{aligned}I_V &= \int_0^{\pi/2} \int_0^3 (4r \cos \theta + 16r \sin \theta) r dr d\theta \\ &= \int_0^{\pi/2} (4 \cos \theta + 16 \sin \theta) d\theta \int_0^3 r^2 dr \\ &= \int_0^{\pi/2} (4 \cos \theta + 16 \sin \theta) d\theta \left[\frac{r^3}{3} \right]_0^3 \\ &= 9 \int_0^{\pi/2} (4 \cos \theta + 16 \sin \theta) d\theta\end{aligned}$$

Finally, integrate with respect to θ :

$$\begin{aligned} I_V &= 9 [4 \sin \theta - 16 \cos \theta]_0^{\pi/2} \\ &= 9[(4(1) - 0) - (0 - 16(1))] \\ &= 9[4 + 16] = 9(20) = 180 \end{aligned}$$

Volume Integral Result: 180.

Part 2. The Surface Integral We compute the flux through the 5 boundary surfaces.

1. Surface S_1 : $x = 0$

Normal $\hat{n} = -\hat{i}$. $\vec{f}(0, y, z) = 0\hat{i} - y^2\hat{j} + 0\hat{k}$.

Flux: $\vec{f} \cdot \hat{n} = 0$.

$$\Phi_1 = 0$$

2. Surface S_2 : $x = 2$

Normal $\hat{n} = \hat{i}$. $\vec{f}(2, y, z) = 8y\hat{i} - y^2\hat{j} + 8z^2\hat{k}$.

Flux integrand: $\vec{f} \cdot \hat{i} = 8y$.

Region is the quarter circle ($r = 3$) in yz -plane.

$$\begin{aligned} \Phi_2 &= \int_0^{\pi/2} \int_0^3 (8r \cos \theta)r dr d\theta = 8 \left(\int \cos \theta d\theta \right) \left(\int r^2 dr \right) \\ &= 8[\sin \theta]_0^{\pi/2} \left[\frac{r^3}{3} \right]_0^3 = 8(1)(9) = 72 \end{aligned}$$

3. Surface S_3 : $y = 0$

Normal $\hat{n} = -\hat{j}$. $\vec{f}(x, 0, z) = 0\hat{i} - 0\hat{j} + 4xz^2\hat{k}$.

Flux integrand: $\vec{f} \cdot (-\hat{j}) = -(-0) = 0$.

$$\Phi_3 = 0$$

4. Surface S_4 : $z = 0$

Normal $\hat{n} = -\hat{k}$. $\vec{f}(x, y, 0) = 2x^2y\hat{i} - y^2\hat{j} + 0\hat{k}$.

Flux integrand: $\vec{f} \cdot (-\hat{k}) = 0$.

$$\Phi_4 = 0$$

5. Surface S_5 : $y^2 + z^2 = 9$ The normal vector to the cylinder is in the yz -plane.

Gradient $\nabla(y^2 + z^2) = 2y\hat{j} + 2z\hat{k}$.

Unit Normal $\hat{n} = \frac{y}{3}\hat{j} + \frac{z}{3}\hat{k}$ (since radius is 3).

Flux integrand:

$$\begin{aligned}\vec{f} \cdot \hat{n} &= (2x^2y\hat{i} - y^2\hat{j} + 4xz^2\hat{k}) \cdot \left(0\hat{i} + \frac{y}{3}\hat{j} + \frac{z}{3}\hat{k}\right) \\ &= -\frac{y^3}{3} + \frac{4xz^3}{3}\end{aligned}$$

We integrate this over the surface. $dS = R d\theta dx = 3 d\theta dx$. Substitute $y = 3 \cos \theta$, $z = 3 \sin \theta$:

$$\begin{aligned}\text{Integrand} &= -\frac{(3 \cos \theta)^3}{3} + \frac{4x(3 \sin \theta)^3}{3} \\ &= -9 \cos^3 \theta + 36x \sin^3 \theta\end{aligned}$$

Now integrate over $x \in [0, 2]$ and $\theta \in [0, \pi/2]$:

$$\begin{aligned}\Phi_5 &= \int_0^2 \int_0^{\pi/2} (-9 \cos^3 \theta + 36x \sin^3 \theta)(3 d\theta dx) \\ \Phi_5 &= 3 \left[\int_0^2 dx \int_0^{\pi/2} -9 \cos^3 \theta d\theta + \int_0^2 36x dx \int_0^{\pi/2} \sin^3 \theta d\theta \right]\end{aligned}$$

Using $\int_0^{\pi/2} \cos^3 \theta d\theta = \frac{2}{3}$ and $\int_0^{\pi/2} \sin^3 \theta d\theta = \frac{2}{3}$:

$$\begin{aligned}\text{Term 1} &= 3(2)(-9) \left(\frac{2}{3}\right) = -36 \\ \text{Term 2} &= 3 \left[\frac{36x^2}{2}\right]_0^2 \left(\frac{2}{3}\right) = 3(72) \left(\frac{2}{3}\right) = 144 \\ \Phi_5 &= 144 - 36 = 108\end{aligned}$$

Total Flux

$$\begin{aligned}\Phi_{total} &= \Phi_1 + \Phi_2 + \Phi_3 + \Phi_4 + \Phi_5 \\ &= 0 + 72 + 0 + 0 + 108 \\ &= 180\end{aligned}$$

Conclusion

Since the Volume Integral (180) equals the Surface Integral (180), the Divergence Theorem is verified.

27 Question 26

Problem Find the shaded area shown in the figure by Green's Theorem in the xy -plane:

$$\text{Area} = \frac{1}{2} \oint_C (xdy - ydx)$$

The region is bounded by $y = 0$, $y = 2 - x^2$, and $y = x$. The intersection of $y = x$ and $y = 2 - x^2$ is at $(1, 1)$. The parabola intersects the x-axis at $(\sqrt{2}, 0)$.

Solution To find the area using Green's Theorem, we use the vector field $\vec{F} = (-y/2, x/2)$ or simply the formula:

$$A = \frac{1}{2} \oint_C (x dy - y dx)$$

We break the path C into three segments $C_1 + C_2 + C_3$.

1. Segment C_1 : Along the x-axis

Path: From $(0, 0)$ to $(\sqrt{2}, 0)$.

Equation: $y = 0 \implies dy = 0$.

Integral:

$$I_1 = \frac{1}{2} \int_0^{\sqrt{2}} (x(0) - (0)dx) = 0$$

2. Segment C_2 : Along the parabola

Path: From $(\sqrt{2}, 0)$ to $A(1, 1)$.

Equation: $y = 2 - x^2$.

Differentials: $dy = -2x dx$.

Substitute into the integral formula:

$$\begin{aligned} x dy - y dx &= x(-2x dx) - (2 - x^2) dx \\ &= (-2x^2 - 2 + x^2) dx \\ &= (-x^2 - 2) dx \end{aligned}$$

Integrate from $x = \sqrt{2}$ to $x = 1$:

$$\begin{aligned}
I_2 &= \frac{1}{2} \int_{\sqrt{2}}^1 (-x^2 - 2) dx \\
&= \frac{1}{2} \left[-\frac{x^3}{3} - 2x \right]_{\sqrt{2}}^1 \\
&= \frac{1}{2} \left(\left(-\frac{1}{3} - 2 \right) - \left(-\frac{2\sqrt{2}}{3} - 2\sqrt{2} \right) \right) \\
&= \frac{1}{2} \left(-\frac{7}{3} - \left(-\frac{8\sqrt{2}}{3} \right) \right) \\
&= \frac{1}{2} \left(\frac{8\sqrt{2} - 7}{3} \right) = \frac{8\sqrt{2} - 7}{6}
\end{aligned}$$

3. Segment C_3 : Along the line $y = x$

Path: From $A(1, 1)$ to $(0, 0)$.

Equation: $y = x \implies dy = dx$.

Substitute into the integral:

$$\begin{aligned}
x dy - y dx &= x(dx) - x(dx) = 0 \\
I_3 &= 0
\end{aligned}$$

Total Area Summing the integrals:

$$\begin{aligned}
\text{Area} &= I_1 + I_2 + I_3 = 0 + \frac{8\sqrt{2} - 7}{6} + 0 \\
\text{Area} &= \frac{8\sqrt{2} - 7}{6} \approx 0.719
\end{aligned}$$

Verification (Standard Integration)

$$\begin{aligned}
A &= \int_0^1 (x - 0) dx + \int_1^{\sqrt{2}} (2 - x^2) dx \\
&= \left[\frac{x^2}{2} \right]_0^1 + \left[2x - \frac{x^3}{3} \right]_1^{\sqrt{2}} \\
&= \frac{1}{2} + \left(\frac{4\sqrt{2}}{3} - \frac{5}{3} \right) \\
&= \frac{3}{6} + \frac{8\sqrt{2} - 10}{6} = \frac{8\sqrt{2} - 7}{6}
\end{aligned}$$

The result is correct.

28 Question 27

Problem

- i) Find the angle between surfaces $x^2 + y^2 + z^2 = 9$ and $z = x^2 + y^2 - 3$ at the point $P(2, -1, 2)$.
ii) Test if any of these scalar functions is a harmonic function. Why?

Solution

i) Angle Between the Surfaces The angle θ between two surfaces is defined as the angle between their normal vectors at the point of intersection. The normal vector to a surface defined by $f(x, y, z) = c$ is the gradient ∇f . Let the scalar functions defining the surfaces be:

$$f(x, y, z) = x^2 + y^2 + z^2 - 9$$

$$g(x, y, z) = x^2 + y^2 - z - 3$$

1. Compute Gradients

$$\nabla f = \frac{\partial f}{\partial x} \hat{i} + \frac{\partial f}{\partial y} \hat{j} + \frac{\partial f}{\partial z} \hat{k} = 2x\hat{i} + 2y\hat{j} + 2z\hat{k}$$

$$\nabla g = \frac{\partial g}{\partial x} \hat{i} + \frac{\partial g}{\partial y} \hat{j} + \frac{\partial g}{\partial z} \hat{k} = 2x\hat{i} + 2y\hat{j} - 1\hat{k}$$

2. Evaluate at Point $P(2, -1, 2)$

Substitute $x = 2, y = -1, z = 2$:

$$\vec{n}_1 = \nabla f(2, -1, 2) = 2(2)\hat{i} + 2(-1)\hat{j} + 2(2)\hat{k} = \langle 4, -2, 4 \rangle$$

$$\vec{n}_2 = \nabla g(2, -1, 2) = 2(2)\hat{i} + 2(-1)\hat{j} - 1\hat{k} = \langle 4, -2, -1 \rangle$$

3. Calculate the Angle

The cosine of the angle is given by:

$$\cos \theta = \frac{|\vec{n}_1 \cdot \vec{n}_2|}{|\vec{n}_1||\vec{n}_2|}$$

Dot Product:

$$\vec{n}_1 \cdot \vec{n}_2 = (4)(4) + (-2)(-2) + (4)(-1) = 16 + 4 - 4 = 16$$

Magnitudes:

$$|\vec{n}_1| = \sqrt{4^2 + (-2)^2 + 4^2} = \sqrt{16 + 4 + 16} = \sqrt{36} = 6$$

$$|\vec{n}_2| = \sqrt{4^2 + (-2)^2 + (-1)^2} = \sqrt{16 + 4 + 1} = \sqrt{21}$$

Substitute into the formula:

$$\cos \theta = \frac{16}{6\sqrt{21}} = \frac{8}{3\sqrt{21}}$$

$$\theta = \arccos \left(\frac{8}{3\sqrt{21}} \right) \approx \arccos(0.5819) \approx 54.41^\circ$$

ii) Harmonic Function Test A function ϕ is harmonic if it satisfies Laplace's Equation: $\nabla^2 \phi = \frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + \frac{\partial^2 \phi}{\partial z^2} = 0$.

Test for $f(x, y, z) = x^2 + y^2 + z^2 - 9$:

$$\frac{\partial^2 f}{\partial x^2} = 2, \quad \frac{\partial^2 f}{\partial y^2} = 2, \quad \frac{\partial^2 f}{\partial z^2} = 2$$

$$\nabla^2 f = 2 + 2 + 2 = 6 \neq 0$$

So, f is **not** harmonic.

Test for $g(x, y, z) = x^2 + y^2 - z - 3$:

$$\frac{\partial^2 g}{\partial x^2} = 2, \quad \frac{\partial^2 g}{\partial y^2} = 2, \quad \frac{\partial^2 g}{\partial z^2} = 0$$

$$\nabla^2 g = 2 + 2 + 0 = 4 \neq 0$$

So, g is **not** harmonic.

Conclusion Neither of the scalar functions defining the surfaces is harmonic because their Laplacians are non-zero constants.

29 Question 28

Problem Verify the Divergence Theorem of Gauss (DTG): $\iiint_V (\nabla \cdot \vec{f}) dV = \oint_S \vec{f} \cdot d\vec{s}$ for the vector field:

$$\vec{f} = (x^2)\hat{i} + (xz^3(y+1))\hat{j}$$

The volume V is the pentahedron shown in the figure, bounded by $x = 0, x = 2, y = 0, z = 0$ and the plane $y + z = 1$.

Solution

Part 1. The Volume Integral First, calculate the divergence $\nabla \cdot \vec{f}$:

$$\begin{aligned}\nabla \cdot \vec{f} &= \frac{\partial}{\partial x}(x^2) + \frac{\partial}{\partial y}(x(y+1)z^3) + \frac{\partial}{\partial z}(0) \\ &= 2x + x(1)z^3 + 0 = 2x + xz^3\end{aligned}$$

The volume V is defined by the limits: $0 \leq x \leq 2, 0 \leq y \leq 1$, and $0 \leq z \leq 1 - y$.

$$\begin{aligned}I_V &= \int_0^2 \int_0^1 \int_0^{1-y} (2x + xz^3) dz dy dx \\ &= \int_0^2 x dx \int_0^1 \left[2z + \frac{z^4}{4} \right]_0^{1-y} dy \\ &= \left[\frac{x^2}{2} \right]_0^2 \int_0^1 \left(2(1-y) + \frac{(1-y)^4}{4} \right) dy \\ &= (2) \int_0^1 \left(2(1-y) + \frac{1}{4}(1-y)^4 \right) dy\end{aligned}$$

Let $u = 1 - y$, then $du = -dy$. Limits change from $1 \rightarrow 0$.

$$\begin{aligned}I_V &= 2 \int_1^0 \left(2u + \frac{u^4}{4} \right) (-du) = 2 \int_0^1 \left(2u + \frac{u^4}{4} \right) du \\ &= 2 \left[u^2 + \frac{u^5}{20} \right]_0^1 \\ &= 2 \left(1 + \frac{1}{20} \right) = 2(1.05) = 2.1\end{aligned}$$

Volume Integral Result: 2.1

Part 2. The Surface Integral We compute the flux Φ through each of the 5 surfaces.

1. Surface S_1 : $x = 0$

Normal $\hat{n} = -\hat{i}$. Field $\vec{f}(0, y, z) = 0\hat{i} + 0\hat{j}$.

Flux: $\vec{f} \cdot \hat{n} = 0$.

$$\Phi_1 = 0$$

2. Surface S_2 : $x = 2$

Normal $\hat{n} = \hat{i}$. Field $\vec{f}(2, y, z) = 4\hat{i} + 2(y+1)z^3\hat{j}$.

Flux integrand: $\vec{f} \cdot \hat{i} = 4$.

Area of the triangle (base 1, height 1): $A = \frac{1}{2}(1)(1) = 0.5$.

$$\Phi_2 = \iint_{S_2} 4 \, dA = 4(0.5) = 2$$

3. Surface S_3 : $y = 0$ This is the rectangle in the xz -plane $(0 \leq x \leq 2, 0 \leq z \leq 1)$

Normal $\hat{n} = -\hat{j}$. Field $\vec{f}(x, 0, z) = x^2\hat{i} + x(1)z^3\hat{j}$.

Flux integrand: $\vec{f} \cdot (-\hat{j}) = -xz^3$.

$$\begin{aligned}\Phi_3 &= \int_0^2 \int_0^1 -xz^3 \, dz \, dx = - \left(\int_0^2 x \, dx \right) \left(\int_0^1 z^3 \, dz \right) \\ \Phi_3 &= - \left[\frac{x^2}{2} \right]_0^2 \left[\frac{z^4}{4} \right]_0^1 = -(2) \left(\frac{1}{4} \right) = -0.5\end{aligned}$$

4. Surface S_4 : $z = 0$

Normal $\hat{n} = -\hat{k}$. Since \vec{f} has no k -component ($\vec{f} \cdot \hat{k} = 0$).

$$\Phi_4 = 0$$

5. Surface S_5 : $y + z = 1$

This surface projects onto the xy -plane as the rectangle $R : 0 \leq x \leq 2, 0 \leq y \leq 1$. The surface is given by $z = 1 - y$. The normal vector $d\vec{s}$ for a surface $z = g(x, y)$ oriented upwards is $\langle -z_x, -z_y, 1 \rangle dA$. Here, $z_x = 0$ and $z_y = -1$.

$$d\vec{s} = \langle 0, -(-1), 1 \rangle dA = \langle 0, 1, 1 \rangle dy \, dx$$

Compute the dot product $\vec{f} \cdot d\vec{s}$:

$$\vec{f} \cdot d\vec{s} = (x^2\hat{i} + x(y+1)z^3\hat{j}) \cdot (0\hat{i} + 1\hat{j} + 1\hat{k}) = x(y+1)z^3$$

Substituting $z = 1 - y$ into the integrand:

$$\text{Integrand} = x(y+1)(1-y)^3$$

$$\Phi_5 = \int_0^2 \int_0^1 x(y+1)(1-y)^3 dy dx$$

Let $u = 1 - y \implies y = 1 - u, dy = -du$. Limits $1 \rightarrow 0$.

$$\begin{aligned} \int_0^1 (y+1)(1-y)^3 dy &= \int_1^0 ((1-u)+1)u^3(-du) \\ &= \int_0^1 (2-u)u^3 du = \int_0^1 (2u^3 - u^4) du \\ &= \left[\frac{2u^4}{4} - \frac{u^5}{5} \right]_0^1 = \frac{1}{2} - \frac{1}{5} = 0.3 \end{aligned}$$

Now integrate with respect to x :

$$\Phi_5 = \int_0^2 x(0.3) dx = 0.3 \left[\frac{x^2}{2} \right]_0^2 = 0.3(2) = 0.6$$

Total Flux

$$\Phi_{total} = \Phi_1 + \Phi_2 + \Phi_3 + \Phi_4 + \Phi_5 = 0 + 2 - 0.5 + 0 + 0.6 = 2.1$$

Conclusion Since the Volume Integral (2.1) equals the Surface Integral (2.1), the Divergence Theorem is verified.

30 Question 29

Problem For the vector function $\vec{f} = x^2 z \hat{i} - yx^2 \hat{j} + zxy \hat{k}$ and S the hemisphere $x^2 + y^2 + z^2 = 9$ where $0 \leq z \leq 3$, verify Stokes' Theorem:

$$\iint_S (\nabla \times \vec{f}) \cdot d\vec{s} = \oint_C \vec{f} \cdot d\vec{r}$$

The boundary C is the circle $x^2 + y^2 = 9$ in the $z = 0$ plane, oriented counter-clockwise.

Solution

Part 1. The Line Integral The path C lies on the plane $z = 0$, so $dz = 0$. Substitute $z = 0$ into the vector field \vec{f} :

$$\vec{f}(x, y, 0) = x^2(0)\hat{i} - yx^2\hat{j} + (0)xy\hat{k} = -yx^2\hat{j}$$

The line integral becomes:

$$\oint_C \vec{f} \cdot d\vec{r} = \oint_C (0dx - yx^2dy + 0dz) = \oint_C -yx^2 dy$$

Parameterize the circle C ($x^2 + y^2 = 9$):

$$x = 3 \cos t, \quad y = 3 \sin t, \quad dy = 3 \cos t dt, \quad t \in [0, 2\pi]$$

Substitute into the integral:

$$\begin{aligned} I &= \int_0^{2\pi} -(3 \sin t)(3 \cos t)^2(3 \cos t) dt \\ &= \int_0^{2\pi} -3 \sin t(9 \cos^2 t)(3 \cos t) dt \\ &= -81 \int_0^{2\pi} \cos^3 t \sin t dt \end{aligned}$$

Let $u = \cos t$, then $du = -\sin t dt$. Limits: $t = 0 \implies u = 1$, $t = 2\pi \implies u = 1$.

$$I = -81 \int_1^1 u^3(-du) = 0$$

Result The line integral is 0.

Part 2. The Surface Integral First, compute the Curl of \vec{f} :

$$\nabla \times \vec{f} = \begin{vmatrix} \hat{i} & \hat{j} & \hat{k} \\ \partial_x & \partial_y & \partial_z \\ x^2 z & -yx^2 & zxy \end{vmatrix}$$

$$\begin{aligned}\hat{i}\text{-component: } & \frac{\partial}{\partial y}(zxy) - \frac{\partial}{\partial z}(-yx^2) = zx - 0 = zx \\ \hat{j}\text{-component: } & \frac{\partial}{\partial z}(x^2z) - \frac{\partial}{\partial x}(zxy) = x^2 - zy \\ \hat{k}\text{-component: } & \frac{\partial}{\partial x}(-yx^2) - \frac{\partial}{\partial y}(x^2z) = -2xy - 0 = -2xy\end{aligned}$$

$$\nabla \times \vec{f} = \langle zx, x^2 - zy, -2xy \rangle$$

The outward unit normal for the sphere $x^2 + y^2 + z^2 = 9$ is $\hat{n} = \frac{1}{3}\langle x, y, z \rangle$. Calculate the dot product $(\nabla \times \vec{f}) \cdot \hat{n}$:

$$\begin{aligned}(\nabla \times \vec{f}) \cdot \hat{n} &= \frac{1}{3} [(zx)(x) + (x^2 - zy)(y) + (-2xy)(z)] \\ &= \frac{1}{3}[zx^2 + x^2y - zy^2 - 2xyz]\end{aligned}$$

We integrate this over the hemisphere. Using spherical coordinates ($x = 3 \sin \phi \cos \theta, y = 3 \sin \phi \sin \theta, z = 3 \cos \phi$) is possible but tedious due to the many terms. Instead, let's analyze the symmetry of the terms over the domain $0 \leq \theta \leq 2\pi$.

The area element is $dS = 9 \sin \phi d\phi d\theta$. The integral of any term with an odd power of x or y (like $\cos \theta$ or $\sin \theta$) over a full circle (0 to 2π) is zero.

Let's check the terms in the numerator: $zx^2 + x^2y - zy^2 - 2xyz$.

1. $zx^2 \propto (\cos \phi)(\sin^2 \phi \cos^2 \theta)$. Contains $\cos^2 \theta$. Integral $\int_0^{2\pi} \cos^2 \theta d\theta = \pi$. This term might be non-zero.
2. $x^2y \propto (\sin^2 \phi \cos^2 \theta)(\sin \phi \sin \theta)$. Contains $\cos^2 \theta \sin \theta$. Let $u = \cos \theta$, $du = -\sin \theta d\theta$. Integral from 1 to 1 is 0.
3. $zy^2 \propto (\cos \phi)(\sin^2 \phi \sin^2 \theta)$. Contains $\sin^2 \theta$. Integral $\int_0^{2\pi} \sin^2 \theta d\theta = \pi$. This term might be non-zero.
4. $2xyz \propto (\sin \phi \cos \theta)(\sin \phi \sin \theta)(\cos \phi)$. Contains $\sin \theta \cos \theta = \frac{1}{2} \sin 2\theta$. Integral over period is 0.

So we only need to integrate the first and third terms: $\frac{1}{3}(zx^2 - zy^2)$.

$$\text{Integrand} = \frac{1}{3}z(x^2 - y^2)$$

Substitute spherical coordinates ($x^2 - y^2 = \rho^2 \sin^2 \phi (\cos^2 \theta - \sin^2 \theta) = \rho^2 \sin^2 \phi \cos(2\theta)$).

$$\iint \frac{1}{3}(3 \cos \phi)[9 \sin^2 \phi \cos(2\theta)](9 \sin \phi) d\phi d\theta$$

The θ integral is $\int_0^{2\pi} \cos(2\theta) d\theta$. Since we are integrating $\cos(2\theta)$ over two full periods (0 to 4π effectively in the argument), the result is zero.

Conclusion

$$\iint_S (\nabla \times \vec{f}) \cdot d\vec{s} = 0$$

Both integrals are 0, verifying Stokes' Theorem.