

# **Solved Problems in Mathematical Methods for Physicists**

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# Determinants and Matrices

# 2

## 2.2.1

Show that matrix multiplication is associative,  $(\mathbf{AB})\mathbf{C} = \mathbf{A}(\mathbf{BC})$

**Solution** The product  $\mathbf{BC}$  is defined because the column of  $\mathbf{B}$  and rows of  $\mathbf{C}$  are same. Suppose  $\mathbf{D} = \mathbf{BC}$  Then element of  $\mathbf{D}$  is of the form

$$d_{ik} = \sum_j b_{ij}c_{jk}$$

Now the product  $\mathbf{AD}$  is defined because the column of  $\mathbf{A}$  and rows of  $\mathbf{D}$  are same. Then element of  $\mathbf{E}$  is of the form

$$e_{lk} = \sum_i a_{li} \left( \sum_j b_{ij}c_{jk} \right)$$

Therefore, the matrix  $\mathbf{E} = \mathbf{A}(\mathbf{BC})$  have the elements  $e_{lk}$ . The product  $\mathbf{AB}$  is defined because the column of  $\mathbf{A}$  and rows of  $\mathbf{B}$  are same. Let,  $\mathbf{D} = \mathbf{AB}$ . Then element of  $\mathbf{D}$  is of the form

$$d_{lj} = \sum_i a_{li}b_{ij}$$

Now the product  $\mathbf{DC}$  is defined because the column of  $\mathbf{D}$  and rows of  $\mathbf{C}$  are same. Let,  $\mathbf{E} = \mathbf{DC}$ . Then element of  $\mathbf{D}$  is of the form

$$e_{lk} = \sum_j \left( \sum_i a_{li}b_{ij} \right) c_{jk}$$

Therefore, the matrix  $\mathbf{E} = (\mathbf{AB})\mathbf{C}$  have the elements  $e_{lk}$  Therefore,

$$\mathbf{A}(\mathbf{BC}) = (\mathbf{AB})\mathbf{C}$$

Hence, matrix multiplication is associative.

## 2.2.2

Show that

$$(\mathbf{A} + \mathbf{B})(\mathbf{A} - \mathbf{B}) = \mathbf{A}^2 - \mathbf{B}^2$$

if and only if  $\mathbf{A}$  and  $\mathbf{B}$  commute

$$[\mathbf{A}, \mathbf{B}] = 0$$

**Solution**

$$(\mathbf{A} + \mathbf{B})(\mathbf{A} - \mathbf{B}) = (\mathbf{A} - \mathbf{B})(\mathbf{A} + \mathbf{B}) = \mathbf{A}(\mathbf{A} + \mathbf{B}) - \mathbf{B}(\mathbf{A} + \mathbf{B})$$

$$(\mathbf{A} + \mathbf{B})(\mathbf{A} - \mathbf{B}) = \mathbf{A}^2 + \mathbf{AB} - \mathbf{BA} - \mathbf{B}^2$$

$$(\mathbf{A} + \mathbf{B})(\mathbf{A} - \mathbf{B}) = \mathbf{A}^2 - \mathbf{B}^2 + (\mathbf{AB} - \mathbf{BA})$$

Because  $\mathbf{A}$  and  $\mathbf{B}$  commute, the term  $(\mathbf{AB} - \mathbf{BA})$  equals to zero, hence is proved.

$$(\mathbf{A} + \mathbf{B})(\mathbf{A} - \mathbf{B}) = \mathbf{A}^2 - \mathbf{B}^2$$

## 2.2.3

- (a) Complex numbers,  $a + ib$ , with  $a$  and  $b$  real, may be represented by (or are isomorphic with)  $2 \times 2$  matrices:

$$a + ib \longleftrightarrow \begin{bmatrix} a & b \\ -b & a \end{bmatrix}$$

Show that this matrix representation is valid for

- (i) addition
  - (ii) multiplication
- (b) Find the matrix corresponding to  $(a + ib)^{-1}$ .

**Solution** (a) Let us start with addition. For complex numbers, we have (straightforwardly)

$$(a + ib) + (c + id) = (a + c) + i(b + d)$$

whereas, if we used matrices we would get

$$\begin{bmatrix} a & b \\ -b & a \end{bmatrix} + \begin{bmatrix} c & d \\ -d & c \end{bmatrix} = \begin{bmatrix} (a + c) & (b + d) \\ -(b + d) & (a + c) \end{bmatrix}$$

which shows that the sum of matrices yields the proper representation of the complex number  $(a + c) + i(b + d)$ . We now handle multiplication in the same manner. First, we have

$$(a + ib)(c + id) = (ac - bd) + i(ad + bc)$$

while matrix multiplication gives

$$\begin{bmatrix} a & b \\ -b & a \end{bmatrix} \begin{bmatrix} c & d \\ -d & c \end{bmatrix} = \begin{bmatrix} (ac - bd) & (ad + bc) \\ -(ad + bc) & (ac - bd) \end{bmatrix}$$

which is again the correct result.

**Solution** (b) Find the matrix corresponding to  $(a + ib)^{-1}$ . We can find the matrix in two ways. We first do standard complex arithmetic

$$(a + ib)^{-1} = \frac{1}{a + ib} = \frac{a - ib}{(a + ib)(a - ib)} = \frac{1}{a^2 + b^2}(a - ib)$$

This corresponds to the  $2 \times 2$  matrix

$$(a + ib)^{-1} \longleftrightarrow \frac{1}{a^2 + b^2} \begin{bmatrix} a & -b \\ b & a \end{bmatrix}$$

Alternatively, we first convert to a matrix representation, and then find the inverse matrix

$$(a + ib)^{-1} \leftrightarrow \begin{bmatrix} a & b \\ -b & a \end{bmatrix}^{-1} = \frac{1}{a^2 + b^2} \begin{bmatrix} a & -b \\ b & a \end{bmatrix}$$

Either way, we obtain the same result.



## 2.2.4

If  $\mathbf{A}$  is an  $n \times n$  matrix, show that

$$\det(-\mathbf{A}) = (-1)^n \det \mathbf{A}.$$

**Solution** An elementary definition of the determinant of a matrix  $\mathbf{A} = (a_{i,j})$  is given by the expression

$$\det(\mathbf{A}) = \sum_{\pi} s(\pi) a_{1,\pi(1)} \cdots a_{n,\pi(n)}$$

where the sum is extended over all permutations of the set  $1, \dots, n$  and  $s(\pi) = \pm 1$  is the sign of the permutation  $\pi$ . Since each summand is the product of exactly  $n$  of the entries of the matrix, if you reverse all the signs each summand—and so the whole sum—will be altered by a factor of  $(-1)^n$ .

## 2.2.5

- (a) The matrix equation  $\mathbf{A}^2 = 0$  does not imply  $\mathbf{A} = 0$ . Show that the most general  $2 \times 2$  matrix whose square is zero may be written as

$$\begin{bmatrix} ab & b^2 \\ -a^2 & -ab \end{bmatrix}$$

where  $a$  and  $b$  are real or complex numbers.

- (b) If  $\mathbf{C} = \mathbf{A} + \mathbf{B}$ , in general

$$\det \mathbf{C} \neq \det \mathbf{A} + \det \mathbf{B}.$$

Construct a specific numerical example to illustrate this inequality.

**Solution** (a) Let

$$\mathbf{A} = \begin{bmatrix} a & b \\ c & d \end{bmatrix}$$

be a  $2 \times 2$  matrix. Then

$$\mathbf{A}^2 = \begin{bmatrix} a^2 + bc & (a+d)b \\ (a+d)c & d^2 + bc \end{bmatrix}$$

Now find  $a, b, c, d$  such that  $a^2 + bc = (a+d)b = (a+d)c = d^2 + bc = 0$ . Note that if  $a+d=0$  and  $ad-bc=0$ , then all these equations are satisfied. For instance, put  $a = -d = 1, b = -c = 1$  or put  $a = d = 0, b = 0, c = 1$ . Then the matrices

$$\begin{bmatrix} 1 & 1 \\ -1 & -1 \end{bmatrix}, \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}$$

are not 0 but their squares are 0.

## 2.2.6

Given

$$\mathbf{K} = \begin{bmatrix} 0 & 0 & i \\ -i & 0 & 0 \\ 0 & -1 & 0 \end{bmatrix}$$

show that

$$\mathbf{K}^n = \mathbf{K}\mathbf{K}\mathbf{K} \cdots (n \text{ factors}) = 1$$

(with the proper choice of  $n, n \neq 0$ ).

**Solution** We calculate for different  $n$

$$\mathbf{K}^2 = \begin{bmatrix} 0 & -i & 0 \\ 0 & 0 & 1 \\ i & 0 & 0 \end{bmatrix} \quad \mathbf{K}^3 = \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix} \quad \mathbf{K}^4 = \begin{bmatrix} 0 & 0 & -i \\ i & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$$

$$\mathbf{K}^5 = \begin{bmatrix} 0 & i & 0 \\ 0 & 0 & -1 \\ -i & 0 & 0 \end{bmatrix} \quad \mathbf{K}^6 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

With this, the answer is  $n = 6$

### 2.2.7

Verify the Jacobi identity,

$$[\mathbf{A}, [\mathbf{B}, \mathbf{C}]] = [\mathbf{B}, [\mathbf{A}, \mathbf{C}]] - [\mathbf{C}, [\mathbf{A}, \mathbf{B}]]$$

**Solution**

$$[\mathbf{A}[\mathbf{B}, \mathbf{C}]] = [\mathbf{A}, \mathbf{BC} - \mathbf{CB}] = \mathbf{A}(\mathbf{BC} - \mathbf{CB}) - (\mathbf{BC} - \mathbf{CB})\mathbf{A}$$

$$[\mathbf{A}[\mathbf{B}, \mathbf{C}]] = \mathbf{A}(\mathbf{BC}) - \mathbf{A}(\mathbf{CB}) - (\mathbf{BC})\mathbf{A} + (\mathbf{CB})\mathbf{A}$$

$$[\mathbf{B}[\mathbf{C}, \mathbf{A}]] = [\mathbf{B}, \mathbf{CA} - \mathbf{AC}] = \mathbf{B}(\mathbf{CA} - \mathbf{AC}) - (\mathbf{CA} - \mathbf{AC})\mathbf{B}$$

$$[\mathbf{B}[\mathbf{C}, \mathbf{A}]] = \mathbf{B}(\mathbf{CA}) - \mathbf{B}(\mathbf{AC}) - (\mathbf{CA})\mathbf{B} + (\mathbf{AC})\mathbf{B}$$

$$[\mathbf{C}[\mathbf{A}, \mathbf{B}]] = [\mathbf{C}, \mathbf{AB} - \mathbf{BA}] = \mathbf{C}(\mathbf{AB} - \mathbf{BA}) - (\mathbf{AB} - \mathbf{BA})\mathbf{C}$$

$$[\mathbf{C}[\mathbf{A}, \mathbf{B}]] = \mathbf{C}(\mathbf{AB}) - \mathbf{C}(\mathbf{BA}) - (\mathbf{AB})\mathbf{C} + (\mathbf{BA})\mathbf{C}$$

$\mathbf{A}, \mathbf{B}, \mathbf{C}$  are obey associative law  $\mathbf{C}(\mathbf{AB}) = (\mathbf{CA})\mathbf{B}$ ,  $\mathbf{C}(\mathbf{BA}) = (\mathbf{CB})\mathbf{A}$ ,  $(\mathbf{AB})\mathbf{C} = \mathbf{A}(\mathbf{BC})$  and  $(\mathbf{BA})\mathbf{C} = \mathbf{B}(\mathbf{AC})$

$$[\mathbf{C}[\mathbf{A}, \mathbf{B}]] = (\mathbf{CA})\mathbf{B} - (\mathbf{CB})\mathbf{A} - \mathbf{A}(\mathbf{BC}) + \mathbf{B}(\mathbf{AC})$$

$$[\mathbf{C}[\mathbf{A}, \mathbf{B}]] = [\mathbf{A}, [\mathbf{B}, \mathbf{C}]] + [\mathbf{B}[\mathbf{C}, \mathbf{A}]] + [\mathbf{C}[\mathbf{A}, \mathbf{B}]]$$

$$= (\mathbf{A}(\mathbf{BC}) - \mathbf{A}(\mathbf{CB}) - (\mathbf{BC})\mathbf{A} + (\mathbf{CB})\mathbf{A}) + (\mathbf{B}(\mathbf{CA}) - \mathbf{B}(\mathbf{AC}) - (\mathbf{CA})\mathbf{B} + (\mathbf{AC})\mathbf{B}) + (\mathbf{CA})\mathbf{B} - (\mathbf{CB})\mathbf{A} - \mathbf{A}(\mathbf{BC}) + \mathbf{B}(\mathbf{AC}) = 0$$

### 2.2.8

Show that the matrices

$$\mathbf{A} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad \mathbf{B} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix}, \quad \mathbf{C} = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

satisfy the commutation relations

$$[\mathbf{A}, \mathbf{B}] = \mathbf{C}, \quad [\mathbf{A}, \mathbf{C}] = 0, \quad \text{and} \quad [\mathbf{B}, \mathbf{C}] = 0$$

**Solution** We simply multiply the matrices

$$\mathbf{C} = [\mathbf{A}, \mathbf{B}] = \mathbf{AB} - \mathbf{BA}$$

$$\begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix} - \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} = \mathbf{C}$$

$$[\mathbf{A}, \mathbf{C}] = \mathbf{AC} - \mathbf{CA} = 0$$

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

$$[\mathbf{B}, \mathbf{C}] = \mathbf{BC} - \mathbf{CB} = 0$$

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

### 2.2.9

Let

$$i = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{bmatrix}, \quad j = \begin{bmatrix} 0 & 0 & 0 & -1 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}, \quad k = \begin{bmatrix} 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{bmatrix}$$

(a)  $i^2 = j^2 = k^2 = -I$ , where  $I$  is the unit matrix.

(b)  $ij = -ji = k$ ,  $jk = -kj = i$ ,  $ki = -ik = j$

These three matrices ( $i$ ,  $j$ , and  $k$ ) plus the unit matrix  $1$  form a basis for quaternions. An alternate basis is provided by the four  $2 \times 2$  matrices,  $i\sigma_1$ ,  $i\sigma_2$ ,  $-i\sigma_3$ , and  $1$ , where the  $\sigma_i$  are the Pauli spin matrices of Example 2.2.1.

### Solution

$$i^2 = j^2 = k^2 = \begin{bmatrix} -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}$$

$$ij = -ji = k = \begin{bmatrix} 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{bmatrix}$$

$$jk = -kj = i = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{bmatrix}$$

$$ki = -ik = j = \begin{bmatrix} 0 & 0 & 0 & -1 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}$$

## 2.2.10

A matrix with elements  $a_{ij} = 0$  for  $j < i$  may be called upper right triangular. The elements in the lower left (below and to the left of the main diagonal) vanish. Show that the product of two upper right triangular matrices is an upper right triangular matrix.

**Solution** We build 2 matrix with terms  $a, b, c, x, y, z$  that can take any number

$$\begin{bmatrix} a & b & c \\ 0 & d & e \\ 0 & 0 & 0 \end{bmatrix} \times \begin{bmatrix} x & y & z \\ 0 & u & w \\ 0 & 0 & 0 \end{bmatrix} = \begin{bmatrix} a \times x & b \times u + a \times y & b \times w + a \times z \\ 0 & d \times u & d \times w \\ 0 & 0 & 0 \end{bmatrix}$$

Hence is demonstrated that the product of two upper right triangular matrices is an upper right triangular matrix.

## 2.2.11

The three Pauli spin matrices are

$$\sigma_1 = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}, \quad \sigma_2 = \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}, \quad \text{and} \quad \sigma_3 = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$

Show that

- (a)  $(\sigma_i)^2 = \hat{1}_2$
- (b)  $\sigma_i \sigma_j = i \sigma_k, (i, j, k) = (1, 2, 3)$  or a cyclic permutation thereof,
- (c)  $\sigma_i \sigma_j + \sigma_j \sigma_i = 2\delta_{ij} \hat{1}_2$ ;  $\hat{1}_2$  is the  $2 \times 2$  unit matrix.

**Solution** For  $i = 1, j = 2, k = 3$

$$\sigma_i \sigma_j = \sigma_1 \sigma_2 = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} = \begin{bmatrix} i & 0 \\ 0 & -i \end{bmatrix} = i \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} = i \sigma_3 = i \sigma_k$$

For  $i = 2, j = 3, k = 1$

$$\sigma_i \sigma_j = \sigma_2 \sigma_3 = \begin{bmatrix} 0 & i \\ i & 0 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} = \begin{bmatrix} 0 & i \\ i & 0 \end{bmatrix} = i \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} = i \sigma_1 = i \sigma_k$$

For  $i = 3, j = 1, k = 2$

$$\sigma_i \sigma_j = \sigma_3 \sigma_1 = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} = i \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix} = i \sigma_2 = i \sigma_k$$

So, we conclude that  $\sigma_i \sigma_j = i \sigma_k$

**Solution** (c) For this proof we need only to work out the commutation relation and use the proofs done in part (a) and (b)

$$\sigma_2 \sigma_1 = \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix} \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} = \begin{bmatrix} -1 & 0 \\ 0 & i \end{bmatrix} = -i \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} = -i \sigma_3$$

$$\sigma_1 \sigma_3 = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} = -i \begin{bmatrix} 0 & i \\ -i & 0 \end{bmatrix} = -i \sigma_2$$

$$\sigma_3 \cdot \sigma_2 = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix} = \begin{bmatrix} 0 & -i \\ -i & 0 \end{bmatrix} = -i \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} = -i \sigma_1$$

$$\left. \begin{aligned} \sigma_i \sigma_j + \sigma_j \sigma_i &= \sigma_i \sigma_j - \sigma_i \sigma_j = 0 \\ \sigma_i \sigma_j + \sigma_j \sigma_i &= 2\sigma_i^2 \end{aligned} \right\} \begin{aligned} &\text{for } j \neq i \\ &\text{for } j = i \end{aligned}$$

since  $\sigma_i^2 = 1$  and using the kronecker delta we have

$$\sigma_i \sigma_j + \sigma_j \sigma_i = 2\delta_{ij}1$$

### 2.2.12

One description of spin-1 particles uses the matrices

$$\mathbf{M}_x = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}, \quad \mathbf{M}_y = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 & -i & 0 \\ i & 0 & -i \\ 0 & i & 0 \end{bmatrix}$$

and

$$\mathbf{M}_z = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1 \end{bmatrix}$$

- (a)  $[\mathbf{M}_x, \mathbf{M}_y] = i\mathbf{M}_z$ , and so on (cyclic permutation of indices).  
Using the Levi-Civita symbol, we may write

$$[\mathbf{M}_i, \mathbf{M}_j] = i \sum_k \varepsilon_{ijk} \mathbf{M}_k$$

- (b)  $\mathbf{M}^2 \equiv \mathbf{M}_x^2 + \mathbf{M}_y^2 + \mathbf{M}_z^2 = 2\mathbf{I}_3$ , where  $\mathbf{I}_3$  is the  $3 \times 3$  unit matrix.

- (c)  $[\mathbf{M}^2, \mathbf{M}_i] = 0$   $[\mathbf{M}_z, \mathbf{L}^+] = \mathbf{L}^+$   $[\mathbf{L}^+, \mathbf{L}^-] = 2\mathbf{M}_z$  where  $\mathbf{L}^+ \equiv \mathbf{M}_x + i\mathbf{M}_y$  and  $\mathbf{L}^- \equiv \mathbf{M}_x - i\mathbf{M}_y$

**Solution** For (a)

$$\mathbf{M}_x \mathbf{M}_y = \frac{1}{2} \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} 0 & -i & 0 \\ i & 0 & -i \\ 0 & i & 0 \end{bmatrix} = \frac{1}{2} \begin{bmatrix} i & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & -i \end{bmatrix}$$

$$\mathbf{M}_y \mathbf{M}_x = \frac{1}{2} \begin{bmatrix} 0 & -i & 0 \\ i & 0 & -i \\ 0 & i & 0 \end{bmatrix} \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix} = \frac{1}{2} \begin{bmatrix} -i & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & i \end{bmatrix}$$

$$\mathbf{M}_x \mathbf{M}_y - \mathbf{M}_y \mathbf{M}_x = \frac{1}{2} \begin{bmatrix} i & 0 & i \\ 0 & 0 & 0 \\ -i & 0 & -i \end{bmatrix} + \frac{1}{2} \begin{bmatrix} i & 0 & i \\ 0 & 0 & 0 \\ -i & 0 & -i \end{bmatrix}$$

$$\mathbf{M}_x \mathbf{M}_y - \mathbf{M}_y \mathbf{M}_x = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1 \end{bmatrix}$$

$$\mathbf{M}_x \mathbf{M}_y - \mathbf{M}_y \mathbf{M}_x = \mathbf{M}_z$$

**Solution** For (b)

$$\mathbf{M}_x^2 = \frac{1}{2} \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 & 0 & 1 \\ 0 & 2 & 0 \\ 1 & 0 & 1 \end{bmatrix}$$

$$\mathbf{M}_z^2 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad \mathbf{M}_y^2 = \frac{1}{2} \begin{bmatrix} 1 & 0 & -1 \\ 0 & 2 & 0 \\ -1 & 0 & 1 \end{bmatrix}$$

Now

$$\mathbf{M}_x^2 + \mathbf{M}_y^2 + \mathbf{M}_z^2 = 2\mathbf{I}$$

**Solution** (c) we substitute

$$\mathbf{M}^2 = \begin{pmatrix} 2 & 0 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 2 \end{pmatrix}, \quad \mathbf{M}_x = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

and

$$[\mathbf{M}^2, \mathbf{M}_x] = \mathbf{M}^2 \mathbf{M}_x - \mathbf{M}_x \mathbf{M}^2$$

$$\mathbf{M}^2 \mathbf{M}_x = \begin{pmatrix} 2 & 0 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 2 \end{pmatrix} \times \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 2 & 0 \\ 2 & 0 & 2 \\ 0 & 2 & 0 \end{pmatrix}$$

$$\mathbf{M}_x \mathbf{M}^2 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} \times \begin{pmatrix} 2 & 0 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 2 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 2 & 0 \\ 2 & 0 & 2 \\ 0 & 2 & 0 \end{pmatrix}$$

$$[\mathbf{M}^2, \mathbf{M}_x] = \mathbf{M}^2 \mathbf{M}_x - \mathbf{M}_x \mathbf{M}^2 = 0$$

Therefore,  $[\mathbf{M}^2, \mathbf{M}_i] = 0$  Now, we substitute

$$\mathbf{M}_z = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1 \end{pmatrix}$$

and

$$\mathbf{L}^+ = \mathbf{M}_x + i\mathbf{M}_y = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 2 & 0 \\ 0 & 0 & 2 \\ 0 & 0 & 0 \end{pmatrix}$$

$$[\mathbf{M}_z, \mathbf{L}^+] = \mathbf{M}_z \mathbf{L}^+ - \mathbf{L}^+ \mathbf{M}_z$$

$$\mathbf{M}_z \mathbf{L}^+ = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1 \end{pmatrix} \times \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 2 & 0 \\ 0 & 0 & 2 \\ 0 & 0 & 0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 2 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\mathbf{L}^+ \mathbf{M}_z = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 2 & 0 \\ 0 & 0 & 2 \\ 0 & 0 & 0 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1 \end{pmatrix} = 0$$

$$[\mathbf{M}_z, \mathbf{L}^+] = \mathbf{M}_z \mathbf{L}^+ - \mathbf{L}^+ \mathbf{M}_z = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 2 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} = \mathbf{L}^+$$

$$[\mathbf{M}_z, \mathbf{L}^+] = \mathbf{M}_z \mathbf{L}^+ - \mathbf{L}^+ \mathbf{M}_z = \mathbf{L}^+$$

Now, substitute

$$\mathbf{L}^+ = \mathbf{M}_x + i\mathbf{M}_y = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 2 & 0 \\ 0 & 0 & 2 \\ 0 & 0 & 0 \end{pmatrix}$$

and

$$\mathbf{L}^- = \mathbf{M}_x - i\mathbf{M}_y = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 & 0 \\ 2 & 0 & 0 \\ 0 & 2 & 0 \end{pmatrix}$$

$$[\mathbf{L}^+, \mathbf{L}^-] = \mathbf{L}^+ \mathbf{L}^- - \mathbf{L}^- \mathbf{L}^+$$

$$\mathbf{L}^+\mathbf{L}^- = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 2 & 0 \\ 0 & 0 & 2 \\ 0 & 0 & 0 \end{pmatrix} \times \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 & 0 \\ 2 & 0 & 0 \\ 0 & 2 & 0 \end{pmatrix} = \begin{pmatrix} 2 & 0 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\mathbf{L}^-\mathbf{L}^+ = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 & 0 \\ 2 & 0 & 0 \\ 0 & 2 & 0 \end{pmatrix} \times \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 2 & 0 \\ 0 & 0 & 2 \\ 0 & 0 & 0 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 2 \end{pmatrix}$$

$$[\mathbf{L}^+, \mathbf{L}^-] = \mathbf{L}^+\mathbf{L}^- - \mathbf{L}^-\mathbf{L}^+ = \begin{pmatrix} 2 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -2 \end{pmatrix} = 2\mathbf{M}_z$$

Therefore,  $[\mathbf{L}^+, \mathbf{L}^-] = \mathbf{L}^+\mathbf{L}^- - \mathbf{L}^-\mathbf{L}^+ = 2\mathbf{M}_z$

### 2.2.13

Repeat Exercise 2.2.12, using the matrices for a spin of 3/2,

$$\mathbf{M}_x = \frac{1}{2} \begin{pmatrix} 0 & \sqrt{3} & 0 & 0 \\ \sqrt{3} & 0 & 2 & 0 \\ 0 & 2 & 0 & \sqrt{3} \\ 0 & 0 & \sqrt{3} & 0 \end{pmatrix}, \quad \mathbf{M}_y = \frac{i}{2} \begin{pmatrix} 0 & -\sqrt{3} & 0 & 0 \\ \sqrt{3} & 0 & -2 & 0 \\ 0 & 2 & 0 & -\sqrt{3} \\ 0 & 0 & \sqrt{3} & 0 \end{pmatrix}$$

and

$$\mathbf{M}_z = \frac{1}{2} \begin{pmatrix} 3 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -3 \end{pmatrix}$$

**Solution** For (a) we consider that  $[\mathbf{M}_x, \mathbf{M}_y]$

$$\begin{aligned} &= \frac{i}{4} \begin{bmatrix} 0 & \sqrt{3} & 0 & 0 \\ \sqrt{3} & 0 & 2 & 0 \\ 0 & 2 & 0 & \sqrt{3} \\ 0 & 0 & \sqrt{3} & 0 \end{bmatrix} \begin{bmatrix} 0 & -\sqrt{3} & 0 & 0 \\ \sqrt{3} & 0 & -2 & 0 \\ 0 & 2 & 0 & -\sqrt{3} \\ 0 & 0 & \sqrt{3} & 0 \end{bmatrix} - \\ &\quad \frac{i}{4} \begin{bmatrix} 0 & -\sqrt{3} & 0 & 0 \\ \sqrt{3} & 0 & -2 & 0 \\ 0 & 2 & 0 & -\sqrt{3} \\ 0 & 0 & \sqrt{3} & 0 \end{bmatrix} \begin{bmatrix} 0 & \sqrt{3} & 0 & 0 \\ \sqrt{3} & 0 & 2 & 0 \\ 0 & 2 & 0 & \sqrt{3} \\ 0 & 0 & \sqrt{3} & 0 \end{bmatrix} \\ &= \frac{i}{2} \begin{bmatrix} 3 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -3 \end{bmatrix} \\ &= i\mathbf{M}_z \end{aligned}$$

Similarly we can show that  $[\mathbf{M}_y, \mathbf{M}_z] = i\mathbf{M}_x$  and  $[\mathbf{M}_z, \mathbf{M}_x] = i\mathbf{M}_y$ . Thus,  $[\mathbf{M}_i, \mathbf{M}_j] = i \sum_k \varepsilon_{ijk} \mathbf{M}_k$  where  $i, j, k$  can take values 1,2,3 or  $x, y, z$ .

**Solution** For (b) we consider that

$$\begin{aligned} \mathbf{M}^2 &\equiv \mathbf{M}_x^2 + \mathbf{M}_y^2 + \mathbf{M}_z^2 \\ &= \frac{1}{4} \begin{bmatrix} 0 & \sqrt{3} & 0 & 0 \\ \sqrt{3} & 0 & 2 & 0 \\ 0 & 2 & 0 & \sqrt{3} \\ 0 & 0 & \sqrt{3} & 0 \end{bmatrix}^2 - \frac{1}{4} \begin{bmatrix} 0 & -\sqrt{3} & 0 & 0 \\ \sqrt{3} & 0 & -2 & 0 \\ 0 & 2 & 0 & -\sqrt{3} \\ 0 & 0 & \sqrt{3} & 0 \end{bmatrix}^2 + \frac{1}{4} \begin{bmatrix} 3 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -3 \end{bmatrix}^2 \end{aligned}$$

$$\begin{aligned}
&= 2 \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \\
&= 2I_3
\end{aligned}$$

**Solution** For (c) we obtain the result from the previous part

$$\begin{aligned}
[\mathbf{M}^2, \mathbf{M}_i] &= [2I_3, \mathbf{M}_i] \\
&= 2I_3 \mathbf{M}_i - 2\mathbf{M}_i I_3 \\
&= 2\mathbf{M}_i - 2\mathbf{M}_i \\
&= 0
\end{aligned}$$

$$\begin{aligned}
[\mathbf{M}_z, \mathbf{L}^+] &= [\mathbf{M}_z, \mathbf{M}_x + i\mathbf{M}_y] \\
&= [\mathbf{M}_z, \mathbf{M}_x] - [i\mathbf{M}_y, \mathbf{M}_z] \\
&= [\mathbf{M}_z, \mathbf{M}_x] - i[\mathbf{M}_y, \mathbf{M}_z] \\
&= i\mathbf{M}_y - i(i\mathbf{M}_x) \\
&= i\mathbf{M}_y + \mathbf{M}_x \\
&= \mathbf{M}_x + i\mathbf{M}_y \\
&= \mathbf{L}^+
\end{aligned}$$

And finally

$$\begin{aligned}
[\mathbf{L}^+, \mathbf{L}^-] &= [\mathbf{M}_x + i\mathbf{M}_y, \mathbf{M}_x - i\mathbf{M}_y] \\
&= [\mathbf{M}_x, \mathbf{M}_x] - [\mathbf{M}_x, i\mathbf{M}_y] + [i\mathbf{M}_y, \mathbf{M}_x] - [i\mathbf{M}_y, i\mathbf{M}_y], \\
&= 0 - i[\mathbf{M}_x, \mathbf{M}_y] - [\mathbf{M}_x, i\mathbf{M}_y] - 0 \\
&= -2i(i\mathbf{M}_z) \\
&= 2\mathbf{M}_z
\end{aligned}$$

### 2.2.14

If  $\mathbf{A}$  is a diagonal matrix, with all diagonal elements different, and  $\mathbf{A}$  and  $\mathbf{B}$  commute, show that  $\mathbf{B}$  is diagonal.

**Solution** Given matrix  $\mathbf{A}$  is diagonal matrix

$$\mathbf{A} = \text{diag}(a_1, a_2, a_3, \dots, a_n)$$

and  $\mathbf{B} = (b_{ij})$ . Here  $\mathbf{A}$  and  $\mathbf{B}$  matrix commute  $\mathbf{AB} = \mathbf{BA}$ , so

$$(a_i - a_j)b_{kl} = 0 \quad \text{for } k \neq l$$

$$b_{kl} = 0 \quad \text{for } k \neq l$$

Hence from the above statement we can say that is also a diagonal matrix

### 2.2.15

If  $\mathbf{A}$  and  $\mathbf{B}$  are diagonal, show that  $\mathbf{A}$  and  $\mathbf{B}$  commute.

**Solution** consider two  $n \times n$  matrices  $\mathbf{A}$  and  $\mathbf{B}$ , which are diagonal.

$$\mathbf{A} = \begin{bmatrix} a_1 & 0 \\ 0 & a_2 \end{bmatrix}, \quad \mathbf{B} = \begin{bmatrix} b_1 & 0 \\ 0 & b_2 \end{bmatrix}$$

$$\mathbf{AB} = \begin{bmatrix} a_1 & 0 \\ 0 & a_2 \end{bmatrix} \begin{bmatrix} b_1 & 0 \\ 0 & b_2 \end{bmatrix} = \begin{bmatrix} a_1 b_1 & 0 \\ 0 & a_2 b_2 \end{bmatrix}$$



$$\mathbf{BA} = \begin{bmatrix} b_1 & 0 \\ 0 & b_2 \end{bmatrix} \begin{bmatrix} a_1 & 0 \\ 0 & a_2 \end{bmatrix} = \begin{bmatrix} b_1 a_1 & 0 \\ 0 & b_2 a_2 \end{bmatrix}$$

Commutative propeirts of addition:

$$\mathbf{A} + \mathbf{B} = \begin{bmatrix} a_1 & 0 \\ 0 & a_2 \end{bmatrix} + \begin{bmatrix} b_1 & 0 \\ 0 & b_2 \end{bmatrix} = \begin{bmatrix} a_1 + b_1 & 0 \\ 0 & a_2 + b_2 \end{bmatrix}$$

$$\mathbf{B} + \mathbf{A} = \begin{bmatrix} b_1 & 0 \\ 0 & b_2 \end{bmatrix} + \begin{bmatrix} a_1 & 0 \\ 0 & a_2 \end{bmatrix} = \begin{bmatrix} b_1 + a_1 & 0 \\ 0 & b_2 + a_2 \end{bmatrix}$$

Hence, diagonal matrices, when added commute.

### 2.2.16

Show that  $\text{Tr}(\mathbf{ABC}) = \text{Tr}(\mathbf{CBA})$  if any two of the three matrices commute.

**Solution** The trace of a matrix is the sum of its diagonal elements. Therefore, the trace of the product of three matrices  $\mathbf{A}$ ,  $\mathbf{B}$ , and  $\mathbf{C}$  is given by

$$\text{Tr}(\mathbf{ABC}) = \sum_{ijk} \mathbf{A}_{ij} \mathbf{B}_{jk} \mathbf{C}_{ki}$$

By using the fact that  $i, j$ , and  $k$  are dummy summation indices with the same range, this sum can be written in the equivalent forms

$$\sum_{ijk} \mathbf{A}_{ij} \mathbf{B}_{jk} \mathbf{C}_{ki} = \sum_{ijk} \mathbf{C}_{ki} \mathbf{A}_{ij} \mathbf{B}_{jk} = \sum_{ijk} \mathbf{B}_{jk} \mathbf{C}_{ki} \mathbf{A}_{ij}$$

But the second and third of these are

$$\sum_{ijk} \mathbf{C}_{ki} \mathbf{A}_{ij} \mathbf{B}_{jk} = \text{Tr}(\mathbf{CAB})$$

and

$$\sum_{ijk} \mathbf{B}_{jk} \mathbf{C}_{ki} \mathbf{A}_{ij} = \text{Tr}(\mathbf{BCA})$$

respectively. Thus, we obtain the relation

$$\text{Tr}(\mathbf{ABC}) = \text{Tr}(\mathbf{CAB}) = \text{Tr}(\mathbf{BCA})$$

### 2.2.17

**2.2.17** Angular momentum matrices satisfy a commutation relation

$$[\mathbf{M}_j, \mathbf{M}_k] = i\mathbf{M}_l \quad j, k, l \text{ cyclic}$$

**Solution** Taking the trace of both sides of the given expression, we have

$$\text{Tr}(i\mathbf{M}_k) = \text{Tr}(\mathbf{M}_i \mathbf{M}_j - \mathbf{M}_j \mathbf{M}_i)$$

Hence

$$i \text{Tr}(\mathbf{M}_k) = \text{Tr}(\mathbf{M}_i \mathbf{M}_j) - \text{Tr}(\mathbf{M}_j \mathbf{M}_i)$$

since  $\text{Tr}(\mathbf{AB}) = \text{Tr}(\mathbf{BA})$ , we see that  $\text{Tr}(\mathbf{M}_k) = 0$  for any  $k$ .

## 2.2.18

**A** and **B** anticommute:  $\mathbf{AB} = -\mathbf{BA}$ . Also,  $\mathbf{A}^2 = \mathbf{I}$ ,  $\mathbf{B}^2 = \mathbf{I}$ . Show that  $\text{Tr}(\mathbf{A}) = \text{Tr}(\mathbf{B}) = 0$ . Note. The Pauli and Dirac matrices are specific examples.

**Solution** Since  $\mathbf{B}^2 = \mathbf{I}$ , **B** is non-singular and its inverse exists. Therefore,  $\mathbf{A} = -\mathbf{B}^{-1}\mathbf{AB}$ . Taking the trace, we get

$$\text{Tr}(\mathbf{A}) = -\text{Tr}(\mathbf{B}^{-1}\mathbf{AB}) = -\text{Tr}(\mathbf{ABB}^{-1}) = -\text{Tr}(\mathbf{A})$$

We see that  $\text{Tr}(\mathbf{A}) = 0$ . Similarly, we find  $\text{Tr}(\mathbf{B}) = 0$

## 2.2.19

- (a) If two nonsingular matrices anticommute, show that the trace of each one is zero. (Nonsingular means that the determinant of the matrix is nonzero.)
- (b) For the conditions of part (a) to hold, **A** and **B** must be  $n \times n$  matrices with  $n$  even. Show that if  $n$  is odd, a contradiction results.

**Solution** For (a) if the matrices are non-singular, then writing  $\mathbf{A} = -\mathbf{BAB}^{-1}$  and taking the trace, we get  $\text{Tr } \mathbf{A} = -\text{Tr } \mathbf{A}$ . Hence  $\text{Tr } \mathbf{A} = 0$ , and the procedure for **B** is analogous.

**Solution** For (b) now, we compute the determinant of both sides of  $\mathbf{AB} = -\mathbf{BA}$ : this yields  $\det \mathbf{A} \det \mathbf{B} = (-1)^N \det \mathbf{B} \det \mathbf{A}$ , where  $N$  stands for size of matrices. Now since the **A**, **B** are non-singular, both sides of the equality are non-zero and the equality is possible only for even  $N$ .

## 2.2.20

If  $\mathbf{A}^{-1}$  has elements

$$(\mathbf{A}^{-1})_{ij} = a_{ij}^{(-1)} = \frac{\mathbf{C}_{ji}}{|\mathbf{A}|}$$

where  $\mathbf{C}_{ji}$  is the  $ji$  th cofactor of  $|\mathbf{A}|$ , show that

$$\mathbf{A}^{-1}\mathbf{A} = \mathbf{I}$$

Hence  $\mathbf{A}^{-1}$  is the inverse of **A** (if  $|\mathbf{A}| \neq 0$ ).

**Solution** We have to consider that

$$\begin{aligned} (\mathbf{A}^{-1}\mathbf{A})_{ij} &= \sum_k a_{ik}^{-1} a_{kj} \\ &= \sum_k \frac{\mathbf{C}_{ki}}{|\mathbf{A}|} a_{kj} \\ &= \frac{1}{|\mathbf{A}|} \sum_k \mathbf{C}_{ki} a_{kj} \\ &= \frac{1}{|\mathbf{A}|} |\mathbf{A}| \delta_{ij} \\ &= \delta_{ij} \end{aligned}$$

Thus,  $A^{-1}A = 1$ . Hence, by definition of inverse of a matrix  $A^{-1}$  is the inverse of  $A$  (if  $|A| \neq 0$ ).

### 2.2.21

Find the matrices  $\mathbf{M}_L$  such that the product  $\mathbf{M}_L \mathbf{A}$  will be  $\mathbf{A}$  but with:

- (a) The  $i$  th row multiplied by a constant  $k$  ( $a_{ij} \rightarrow ka_{ij}, j = 1, 2, 3, \dots$ )
- (b) The  $i$  th row replaced by the original  $i$  th row minus a multiple of the  $m$  th row ( $a_{ij} \rightarrow a_{ij} - Ka_{mj}, i = 1, 2, 3, \dots$ )
- (c) The  $i$  th and  $m$  th rows interchanged ( $a_{ij} \rightarrow a_{mj}, a_{mj} \rightarrow a_{ij}, j = 1, 2, 3, \dots$ )

**Solution** For (a) Here  $\mathbf{M}_L$  will be the identity matrix the  $i$  th row multiplied by  $k$ , i.e.,  $\mathbf{M}_L$  is given by

$$\begin{bmatrix} 1 & 0 & \cdots & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & k & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 0 & \cdots & 1 \end{bmatrix}$$

**Solution** For (b) Here  $\mathbf{M}_L$  will be the identity matrix with a change which is that the entry in the  $i$  th row and  $m$  th column will be  $-k$  instead of 0. Note that, we have obtained this matrix from the identity matrix by replacing the  $i$  th row by the original  $i$  th row minus a multiple of the  $m$  th row.

$$\begin{bmatrix} 1 & 0 & \cdots & 0 & \cdots & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 & \cdots & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 & \cdots & -k & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 0 & \cdots & 0 & \cdots & 1 \end{bmatrix}$$

**Solution** For (c) Here we obtain the matrix  $\mathbf{M}_L$  from the identity matrix by just inter changing the  $i$  th row and  $m$  th row.

$$\begin{bmatrix} 1 & 0 & \cdots & 0 & \cdots & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 & \cdots & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 0 & \cdots & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 & \cdots & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 0 & \cdots & 0 & \cdots & 1 \end{bmatrix}$$

## 2.2.22

Find the matrices  $\mathbf{M}_R$  such that the product  $\mathbf{A}\mathbf{M}_R$  will be  $\mathbf{A}$  but with:

- (a) The  $i$  th column multiplied by a constant  $k$  ( $a_{ji} \rightarrow ka_{ji}, j = 1, 2, 3, \dots$ )
- (b) The  $i$  th column replaced by the original  $i$  th column minus a multiple of the  $m^{\text{th}}$  column ( $a_{ji} \rightarrow a_{ji} - ka_{jm}, j = 1, 2, 3, \dots$ )
- (c) The  $i$  th and  $m$  th columns interchanged ( $a_{ji} \rightarrow a_{jm}, a_{jm} \rightarrow a_{ji}, j = 1, 2, 3, \dots$ )

**Solution** For (a), here  $\mathbf{M}_L$  will be the identity matrix the  $i$  th row multiplied by  $k$ , i.e.,  $\mathbf{M}_L$  is given by

$$\begin{bmatrix} 1 & 0 & \cdots & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & k & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 0 & \cdots & 1 \end{bmatrix}$$

**Solution** For (b), here  $\mathbf{M}_L$  will be the identity matrix with a change which is that the entry in the  $i$  th row and  $m^{\text{th}}$  column will be  $-k$  instead of 0. Note that, we have obtained this matrix from the identity matrix by replacing the  $i$  th row by the original  $i$  th row minus a multiple of the  $m$  th row.

$$\begin{bmatrix} 1 & 0 & \cdots & 0 & \cdots & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 & \cdots & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 & \cdots & -k & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 0 & \cdots & 0 & \cdots & 1 \end{bmatrix}$$

**Solution** For (c), here we obtain the matrix  $\mathbf{M}_L$  from the identity matrix by just inter changing the  $i$  th row and  $m$  th row.

$$\begin{bmatrix} 1 & 0 & \cdots & 0 & \cdots & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 & \cdots & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 0 & \cdots & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 & \cdots & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 0 & \cdots & 0 & \cdots & 1 \end{bmatrix}$$

## 2.2.23

Find the inverse of

$$\mathbf{A} = \begin{bmatrix} 3 & 2 & 1 \\ 2 & 2 & 1 \\ 1 & 1 & 4 \end{bmatrix}$$

**Solution** Calculating  $\mathbf{A}^{-1}$

$$\mathbf{A}^{-1} = \frac{1}{7} \begin{bmatrix} 7 & -7 & 0 \\ -7 & 11 & -1 \\ 0 & -1 & 2 \end{bmatrix}$$

## 2.2.24

Matrices are far too useful to remain the exclusive property of physicists. They may appear wherever there are linear relations. For instance, in a study of population movement the initial fraction of a fixed population in each of  $n$  areas (or industries or religions, etc.) is represented by an  $n$ -component column vector  $\mathbf{P}$ .

The movement of people from one area to another in a given time is described by an  $n \times n$  (stochastic) matrix  $\mathbf{T}$ . Here  $T_{ij}$  is the fraction of the population in the  $j$ th area that moves to the  $i$ th area. (Those not moving are covered by  $i = j$ .) With  $\mathbf{P}$  describing the initial population distribution, the final population distribution is given by the matrix equation  $\mathbf{TP} = \mathbf{Q}$ . From its definition,  $\sum_{i=1}^n P_i = 1$

(a) Show that conservation of people requires that

$$\sum_{i=1}^n T_{ij} = 1, \quad j = 1, 2, \dots, n$$

(b) Prove that

$$\sum_{i=1}^n Q_i = 1$$

continues the conservation of people.

**Solution** For (a) The equation of part states that  $\mathbf{T}$  moves people from area  $j$  but does not change their total number.

**Solution** For (b) Write the component equation  $\sum_j T_{ij} P_j = Q_i$  and sum over  $i$ . This summation replaces  $T_{ij}$  by unity, leaving that the sum over  $P_j$  equals the sum over  $Q_i$ , hence conserving people.

## 2.2.25

Given a  $6 \times 6$  matrix  $\mathbf{A}$  with elements  $a_{ij} = 0.5^{|i-j|}$ ,  $i, j = 0, 1, 2, \dots, 5$ , find  $\mathbf{A}^{-1}$

$$\mathbf{A} = \begin{bmatrix} 1 & 0.5 & 0.5^2 & 0.5^3 & 0.5^4 & 0.5^5 \\ 0.5 & 1 & 0.5 & 0.5^2 & 0.5^3 & 0.5^4 \\ 0.5^2 & 0.5 & 1 & 0.5 & 0.5^2 & 0.5^3 \\ 0.5^3 & 0.5^2 & 0.5 & 1 & 0.5 & 0.5^2 \\ 0.5^4 & 0.5^3 & 0.5^2 & 0.5 & 1 & 0.5 \\ 0.5^5 & 0.5^4 & 0.5^3 & 0.5^2 & 0.5 & 1 \end{bmatrix}$$

**Solution**

$$\mathbf{A}^{-1} = \frac{1}{3} \begin{bmatrix} 4 & -2 & 0 & 0 & 0 & 0 \\ -2 & 5 & -2 & 0 & 0 & 0 \\ 0 & -2 & 5 & -2 & 0 & 0 \\ 0 & 0 & -2 & 5 & -2 & 0 \\ 0 & 0 & 0 & -2 & 5 & -2 \\ 0 & 0 & 0 & 0 & -2 & 4 \end{bmatrix}$$

**2.2.26**

Show that the product of two orthogonal matrices is orthogonal.

**Solution** Let  $Q$  and  $P$  be orthogonal matrices. Therefore  $\mathbf{Q}^T \mathbf{Q} = I$  and  $\mathbf{P}^T \mathbf{P} = I$ . We have that

$$(\mathbf{PQ})^T (\mathbf{PQ}) = \mathbf{Q}^T \mathbf{P}^T \mathbf{P} \mathbf{Q} = \mathbf{Q}^T \mathbf{Q} = I$$

Therefore, a product of two orthogonal matrix is an orthogonal matrix.

**2.2.27**

If  $A$  is orthogonal, show that its determinant  $= \pm 1$ .

**Solution** We know that

$$\det \mathbf{A}^T = \det \mathbf{A}$$

$$\mathbf{A}^T \mathbf{A} = I$$

$$\det \mathbf{A}^T = \det I = 1$$

$$\det \mathbf{A}^T \mathbf{A} \det \mathbf{A}^T \det \mathbf{A}$$

$$(\det \mathbf{A})^2 = \det \mathbf{A} \det \mathbf{A}^T = \det \mathbf{A}^T \det \mathbf{A} = \det \mathbf{A}^T \mathbf{A} = 1$$

So we must have

$$\det \mathbf{A} = \pm 1$$

**2.2.28**

Show that the trace of the product of a symmetric and an antisymmetric matrix is zero.

**Solution** If  $\tilde{\mathbf{A}} = -\mathbf{A}$ ,  $\tilde{\mathbf{S}} = \mathbf{S}$ , then

$$\text{Tr}(\tilde{\mathbf{S}}\tilde{\mathbf{A}}) = \text{Tr}(\mathbf{S}\mathbf{A}) = \text{Tr}(\tilde{\mathbf{A}}\tilde{\mathbf{S}}) = -\text{Tr}(\mathbf{A}\mathbf{S})$$

**2.2.29**

$A$  is  $2 \times 2$  and orthogonal. Find the most general form of

$$\mathbf{A} = \begin{bmatrix} a & b \\ c & d \end{bmatrix}$$

**Solution** From  $\tilde{\mathbf{A}} = \mathbf{A}^{-1}$  and  $\det(\mathbf{A}) = 1$  we have

$$\mathbf{A}^{-1} = \begin{bmatrix} a_{22} & -a_{12} \\ -a_{21} & a_{11} \end{bmatrix} = \tilde{\mathbf{A}} = \begin{bmatrix} a_{11} & a_{21} \\ a_{12} & a_{22} \end{bmatrix}$$

This gives  $\det(\mathbf{A}) = a_{11}^2 + a_{12}^2 = 1$ , hence

$$a_{11} = \cos \theta = a_{22}, \quad a_{12} = \sin \theta = -a_{21},$$

the standard  $2 \times 2$  rotation matrix.

### 2.2.30

Show that

$$\det(\mathbf{A}^*) = (\det \mathbf{A})^* = \det(\mathbf{A}^\dagger)$$

**Solution** We calculate the determinant of  $\mathbf{A}^*$

$$\det(\mathbf{A}^*) = \sum_{i_k} \varepsilon_{i_1 i_2 \dots i_n} a_{1i_1}^* a_{2i_2}^* \dots a_{ni_n}^* = \left( \sum_{i_k} \varepsilon_{i_1 i_2 \dots i_n} a_{1i_1} a_{2i_2} \dots a_{ni_n} \right)^*$$

Because, for any  $\mathbf{A}$ ,

$$\det(\mathbf{A}) = \det(\tilde{\mathbf{A}}), \det(\mathbf{A}^*) = \det(\mathbf{A}^\dagger)$$

### 2.2.31

Three angular momentum matrices satisfy the basic commutation relation

$$[\mathbf{J}_x, \mathbf{J}_y] = i\mathbf{J}_z$$

(and cyclic permutation of indices). If two of the matrices have real elements, show that the elements of the third must be pure imaginary.

**Solution** We know that basic commutation relation is  $[\mathbf{J}_i, \mathbf{J}_j] = i\mathbf{J}_k$ , where  $i, j$  and  $k$  are indices in cyclic permutation. Here it is clear that  $\mathbf{J}_x, \mathbf{J}_y$  are real, so also must be their commutator. So according to commutator rule it requires that  $\mathbf{J}_z$  be pure imaginary.

### 2.2.32

Show that  $(\mathbf{AB})^\dagger = \mathbf{B}^\dagger \mathbf{A}^\dagger$

**Solution**

$$(\mathbf{AB})^\dagger = \widetilde{\mathbf{A}^* \mathbf{B}^*} = \tilde{\mathbf{B}}^* \tilde{\mathbf{A}}^* = \mathbf{B}^\dagger \mathbf{A}^\dagger$$

### 2.2.33

A matrix  $\mathbf{C} = \mathbf{S}^\dagger \mathbf{S}$ . Show that the trace is positive definite unless  $\mathbf{S}$  is the null matrix, in which case  $\text{Tr}(\mathbf{C}) = 0$ .

**Solution** As

$$C_{jk} = \sum_n S_{nj}^* S_{nk}$$

$$\text{Tr}(\mathbf{C}) = \sum_{nj} |S_{nj}|^2$$

## 2.2.34

If  $\mathbf{A}$  and  $\mathbf{B}$  are Hermitian matrices, show that  $(\mathbf{AB} + \mathbf{BA})$  and  $i(\mathbf{AB} - \mathbf{BA})$  are also Hermitian.

**Solution** If  $\mathbf{A}^\dagger = \mathbf{A}$ ,  $\mathbf{B}^\dagger = \mathbf{B}$ , then

$$(\mathbf{AB} + \mathbf{BA})^\dagger = \mathbf{B}^\dagger \mathbf{A}^\dagger + \mathbf{A}^\dagger \mathbf{B}^\dagger = \mathbf{AB} + \mathbf{BA}$$

$$-i(\mathbf{B}^\dagger \mathbf{A}^\dagger - \mathbf{A}^\dagger \mathbf{B}^\dagger) = i(\mathbf{AB} - \mathbf{BA})$$

## 2.2.35

The matrix  $\mathbf{C}$  is not Hermitian. Show that then  $\mathbf{C} + \mathbf{C}^\dagger$  and  $i(\mathbf{C} - \mathbf{C}^\dagger)$  are Hermitian. This means that a non-Hermitian matrix may be resolved into two Hermitian parts,

$$\mathbf{C} = \frac{1}{2}(\mathbf{C} + \mathbf{C}^\dagger) + \frac{1}{2i}i(\mathbf{C} - \mathbf{C}^\dagger)$$

This decomposition of a matrix into two Hermitian matrix parts parallels the decomposition of a complex number  $z$  into  $x + iy$ , where  $x = (z + z^*)/2$  and  $y = (z - z^*)/2i$

**Solution** If  $\mathbf{C}^\dagger \neq \mathbf{C}$ , then

$$(i\mathbf{C}_-)^\dagger \equiv (\mathbf{C}^\dagger - \mathbf{C})^\dagger = \mathbf{C} - \mathbf{C}^\dagger = -i\mathbf{C}_-,$$

$$(\mathbf{C}_-)^\dagger = \mathbf{C}_-$$

$$\mathbf{C}_+^\dagger = \mathbf{C}_+ = \mathbf{C} + \mathbf{C}^\dagger$$

## 2.2.36

$\mathbf{A}$  and  $\mathbf{B}$  are two noncommuting Hermitian matrices:

$$\mathbf{AB} - \mathbf{BA} = i\mathbf{C}$$

Prove that  $\mathbf{C}$  is Hermitian.

**Solution** Let's consider

$$-i\mathbf{C}^\dagger = (\mathbf{AB} - \mathbf{BA})^\dagger$$

$$-i\mathbf{C}^\dagger = \mathbf{B}^\dagger \mathbf{A}^\dagger - \mathbf{A}^\dagger \mathbf{B}^\dagger$$

$$-i\mathbf{C}^\dagger = \mathbf{BA} - \mathbf{AB}$$

$$-i\mathbf{C}^\dagger = -i\mathbf{C}$$

## 2.2.37

Two matrices  $\mathbf{A}$  and  $\mathbf{B}$  are each Hermitian. Find a necessary and sufficient condition for their product  $\mathbf{AB}$  to be Hermitian.

**Solution**

$$(\mathbf{AB})^\dagger = \mathbf{B}^\dagger \mathbf{A}^\dagger = \mathbf{BA} = \mathbf{AB}$$

With this, we can say that  $[\mathbf{A}, \mathbf{B}] = 0$



## 2.2.38

Show that the reciprocal (that is, inverse) of a unitary matrix is unitary.

## Solution

$$\begin{aligned} (\mathbf{U}^\dagger)^\dagger &= \mathbf{U} \\ (\mathbf{U}^\dagger)^\dagger &= (\mathbf{U}^{-1})^\dagger \end{aligned}$$

## 2.2.39

Prove that the direct product of two unitary matrices is unitary.

## Solution

$$\begin{aligned} (\mathbf{U}_1 \mathbf{U}_2)^\dagger &= \mathbf{U}_2^\dagger \mathbf{U}_1^\dagger \\ (\mathbf{U}_1 \mathbf{U}_2)^\dagger &= \mathbf{U}_2^{-1} \mathbf{U}_1^{-1} \\ (\mathbf{U}_1 \mathbf{U}_2)^\dagger &= (\mathbf{U}_1 \mathbf{U}_2)^{-1} \end{aligned}$$

## 2.2.40

If  $\sigma$  is the vector with the  $\sigma_i$  as components given in Eq. (2.61), and  $p$  is an ordinary vector, show that

$$(\sigma \cdot p)^2 = p^2 \hat{1}_2$$

where  $\hat{1}_2$  is a  $2 \times 2$  unit matrix.

## Solution

$$\begin{aligned} (\mathbf{p} \cdot \boldsymbol{\sigma})^2 &= (p_x \sigma_1 + p_y \sigma_2 + p_z \sigma_3)^2 \\ p_x^2 \sigma_1^2 + p_y^2 \sigma_2^2 + p_z^2 \sigma_3^2 + p_x p_y (\sigma_1 \sigma_2 + \sigma_2 \sigma_1) + p_x p_z (\sigma_1 \sigma_3 + \sigma_3 \sigma_1) \\ &\quad + p_y p_z (\sigma_1 \sigma_2 + \sigma_2 \sigma_1) = p_x^2 + p_y^2 + p_z^2 = \mathbf{p}^2 \end{aligned}$$

## 2.2.41

Use the equations for the properties of direct products, Eqs. (2.57) and (2.58), to show that the four matrices  $\gamma^\mu, \mu = 0, 1, 2, 3$ , satisfy the conditions listed in Eqs. (2.74) and (2.75).

**Solution** Writing  $\gamma^0 = \sigma_3 \otimes \mathbf{1}$  and  $\gamma^i = \gamma \otimes \sigma_i (i = 1, 2, 3)$ , where

$$\gamma = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}$$

and noting from Eq. (2.57) that if  $\mathbf{C} = \mathbf{A} \otimes \mathbf{B}$  and  $\mathbf{C}' = \mathbf{A}' \otimes \mathbf{B}'$  then  $\mathbf{C}\mathbf{C}' = \mathbf{A}\mathbf{A}' \otimes \mathbf{B}\mathbf{B}'$

$$(\gamma^0)^2 = \sigma_3^2 \otimes \mathbf{1}_2^2 = \hat{1}_2 \otimes \mathbf{1}_2 = \hat{1}_4, \quad (\gamma^i)^2 = \gamma^2 \otimes \sigma_i^2 = (-\hat{1}_2) \otimes \mathbf{1}_2 = -\hat{1}_4$$

$$\gamma^0 \gamma^i = \sigma_3 \gamma \otimes \mathbf{1}_2 \sigma_i = \sigma_1 \otimes \sigma_i, \quad \gamma^i \gamma^0 = \gamma \sigma_3 \otimes \sigma_i \mathbf{1}_2 = (-\sigma_1) \otimes \sigma_i$$

$$\gamma^i \gamma^j = \gamma^2 \otimes \sigma_i \sigma_j \quad \gamma^j \gamma^i = \gamma^2 \otimes \sigma_j \sigma_i$$

It is obvious from the second line of the above equation set that  $\gamma^0\gamma^i + \gamma^i\gamma^0 = 0$ ; from the third line of the equation set we find  $\gamma^i\gamma^j + \gamma^j\gamma^i$  is zero if  $j \neq i$  because then  $\sigma_j\sigma_i = -\sigma_i\sigma_j$

**2.2.42**

Show that  $\gamma^5$ , Eq. (2.76), anticommutes with all four  $\gamma^\mu$ .

**Solution**

$$\gamma^0 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}, \quad \gamma^1 = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 \\ -1 & 0 & 0 & 0 \end{bmatrix}, \quad \gamma^2 = \begin{bmatrix} 0 & 0 & 0 & -i \\ 0 & 0 & i & 0 \\ 0 & i & 0 & 0 \\ -i & 0 & 0 & 0 \end{bmatrix}$$

$$\gamma^3 = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \\ -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \quad \text{and} \quad \gamma^5 = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

$$\gamma^0\gamma^5 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{bmatrix}$$

$$\gamma^5\gamma^0 = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix} = \begin{bmatrix} 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

$$\gamma^1\gamma^5 = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 \\ -1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & -1 & 0 \end{bmatrix}$$

$$\gamma^5\gamma^1 = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 \\ -1 & 0 & 0 & 0 \end{bmatrix} = \begin{bmatrix} 0 & -1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

$$\gamma^2\gamma^5 = \begin{bmatrix} 0 & 0 & 0 & -i \\ 0 & 0 & i & 0 \\ 0 & i & 0 & 0 \\ -i & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} = \begin{bmatrix} 0 & -i & 0 & 0 \\ i & 0 & 0 & 0 \\ 0 & 0 & 0 & i \\ 0 & 0 & -i & 0 \end{bmatrix}$$

$$\gamma^5\gamma^2 = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 & 0 & 0 & -i \\ 0 & 0 & i & 0 \\ 0 & i & 0 & 0 \\ -i & 0 & 0 & 0 \end{bmatrix} = \begin{bmatrix} 0 & i & 0 & 0 \\ -i & 0 & 0 & 0 \\ 0 & 0 & 0 & -i \\ 0 & 0 & i & 0 \end{bmatrix}$$

$$\gamma^3\gamma^5 = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \\ -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\gamma^5\gamma^3 = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \\ -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} = \begin{bmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}$$

This shows that  $\gamma^5$  anticommutes with all four  $\gamma^\mu$  ( $\mu = 0, 1, 2, 3$ )

## 2.2.43

In this problem, the summations are over  $\mu = 0, 1, 2, 3$ . Define  $g_{\mu\nu} = g^{\mu\nu}$  by the relations

$$g_{00} = 1; \quad g_{kk} = -1, \quad k = 1, 2, 3; \quad g_{\mu\nu} = 0, \quad \mu \neq \nu$$

and define  $\gamma_\mu$  as  $\sum g_{\nu\mu} \gamma^\nu$ . Using these definitions, show that

$$(a) \quad \sum \gamma_\mu \gamma^\alpha \gamma^\mu = -2\gamma^\alpha$$

$$(b) \quad \sum \gamma_\mu \gamma^\alpha \gamma^\beta \gamma^\mu = 4g^{\alpha\beta}$$

$$(c) \quad \sum \gamma_\mu \gamma^\alpha \gamma^\beta \gamma^\nu \gamma^\mu = -2\gamma^\nu \gamma^\beta \gamma^\alpha$$

**Solution** No solution yet.

## 2.2.44

If  $\mathbf{M} = \frac{1}{2} (1 + \gamma^5)$ , where  $\gamma^5$  is given in Eq. (2.76), show that

$$\mathbf{M}^2 = \mathbf{M}$$

Note that this equation is still satisfied if  $\gamma$  is replaced by any other Dirac matrix listed in Eq. (2.76)

**Solution** Consider  $\mathbf{M}^2 = \left[ \frac{1}{2} (1 + \gamma^5) \right]^2$

$$= \frac{1}{4} \left( \hat{1}_4 + 2\gamma^5 + (\gamma^5)^2 \right)$$

$$= \frac{1}{4} \left( \hat{1}_4 + 2\gamma^5 + \hat{1}_4 \right)$$

$$= \frac{1}{4} \left( 2\hat{1}_4 + 2\gamma^5 \right)$$

$$= \frac{1}{2} \left( \hat{1}_4 + \gamma^5 \right)$$

$$= \mathbf{M}$$

Thus,  $\mathbf{M}^2 = \mathbf{M}$

## 2.2.45

Prove that the 16 Dirac matrices form a linearly independent set.

**Solution** No solution yet.

## 2.2.46

If we assume that a given  $4 \times 4$  matrix  $\mathbf{A}$  (with constant elements) can be written as a linear combination of the 16 Dirac matrices (which we denote here as  $\Gamma_i$ )

$$\mathbf{A} = \sum_{i=1}^{16} c_i \Gamma_i$$

show that

$$c_i \sim \text{trace}(\mathbf{A} \Gamma_i)$$

The matrix  $\mathbf{C} = i\gamma^2\gamma^0$  is sometimes called the charge conjugation matrix. Show that  $\mathbf{C}\gamma^\mu\mathbf{C}^{-1} = -(\gamma^\mu)^T$

**Solution** No solution yet.

## 2.2.47

The matrix  $\mathbf{C} = i\gamma^2\gamma^0$  is sometimes called the charge conjugation matrix. Show that  $\mathbf{C}\gamma^\mu\mathbf{C}^{-1} = -(\gamma^\mu)^T$

**Solution** Here

$$\gamma^0 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}, \quad \gamma^1 = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 \\ -1 & 0 & 0 & 0 \end{bmatrix}, \quad \gamma^2 = \begin{bmatrix} 0 & 0 & 0 & -i \\ 0 & 0 & i & 0 \\ 0 & i & 0 & 0 \\ -i & 0 & 0 & 0 \end{bmatrix}$$

$$\gamma^3 = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \\ -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

$$\text{Consider } \mathbf{C}\gamma^0\mathbf{C}^{-1} = i\gamma^2\gamma^0\gamma^0(i\gamma^2\gamma^0)^{-1}$$

$$\begin{aligned} &= \gamma^2\gamma^0\gamma^0(\gamma^0)^{-1}(\gamma^2)^{-1} \\ &= -\gamma^0 \\ &= -(\gamma^0)^T \\ \mathbf{C}\gamma^1\mathbf{C}^{-1} &= i\gamma^2\gamma^0\gamma^1(i\gamma^2\gamma^0)^{-1} \\ &= \gamma^2\gamma^0\gamma^1(\gamma^0)^{-1}(\gamma^2)^{-1} \\ &= \gamma^1 \\ &= -(\gamma^1)^T \end{aligned}$$

$$\begin{aligned} \mathbf{C}\gamma^2\mathbf{C}^{-1} &= i\gamma^2\gamma^0\gamma^2(i\gamma^2\gamma^0)^{-1} \\ &= \gamma^2\gamma^0\gamma^2(\gamma^0)^{-1}(\gamma^2)^{-1} \\ &= -\gamma^2 \\ &= -(\gamma^2)^T \end{aligned}$$

$$\begin{aligned} \mathbf{C}\gamma^3\mathbf{C}^{-1} &= i\gamma^2\gamma^0\gamma^3(i\gamma^2\gamma^0)^{-1} \\ &= \gamma^2\gamma^0\gamma^3(\gamma^0)^{-1}(\gamma^2)^{-1} \\ &= \gamma^3 \\ &= -(\gamma^3)^T \end{aligned}$$

$$\text{Thus, } \mathbf{C}\gamma^\mu\mathbf{C}^{-1} = -(\gamma^\mu)^T \quad (\mu = 0, 1, 2, 3)$$

## 2.2.48

- (a) Show that, by substitution of the definitions of the  $\gamma^\mu$  matrices from Eqs. (2.70) and (2.72), that the Dirac equation, Eq. (2.73), takes the following form when written as  $2 \times 2$  blocks (with  $\psi_L$  and  $\psi_S$  column vectors of dimension 2). Here  $L$  and  $S$  stand, respectively, for "large" and "small" because of their relative size in the nonrelativistic limit):

$$\begin{bmatrix} mc^2 - E & c(\sigma_1 p_1 + \sigma_2 p_2 + \sigma_3 p_3) \\ -c(\sigma_1 p_1 + \sigma_2 p_2 + \sigma_3 p_3) & -mc^2 - E \end{bmatrix} \begin{bmatrix} \psi_L \\ \psi_S \end{bmatrix} = 0$$

- (b) To reach the nonrelativistic limit, make the substitution  $E = mc^2 + \varepsilon$  and approximate  $-mc^2 - \varepsilon$  by  $-2mc^2$ . Then write the matrix equation as two simultaneous two-component equations and show that they can be rearranged to yield

$$\frac{1}{2m} (p_1^2 + p_2^2 + p_3^2) \psi_L = \varepsilon \psi_L$$

which is just the Schrödinger equation for a free particle.

- (c) Explain why it is reasonable to call  $\psi_L$  and  $\psi_S$  "large" and "small."

**Solution** No solution yet.

## 2.2.49

Show that it is consistent with the requirements that they must satisfy to take the Dirac gamma matrices to be (in  $2 \times 2$  block form)

$$\gamma^0 = \begin{bmatrix} 0 & \mathbf{1}_2 \\ \mathbf{1}_2 & 0 \end{bmatrix}, \quad \gamma^i = \begin{bmatrix} 0 & \sigma_i \\ -\sigma_i & 0 \end{bmatrix}, \quad (i = 1, 2, 3)$$

This choice for the gamma matrices is called the Weyl representation.

**Solution** If  $C = A \otimes B$  and  $C' = A' \otimes B'$  then  $CC' = AA' \otimes BB'$  we have

$$\begin{aligned} (\gamma^0)^2 &= \sigma_2^2 \otimes \hat{1}_2^2 \\ &= \hat{1}_2 \otimes \hat{1}_2 \quad \text{as } \sigma_i^2 = 1 \\ &= \hat{1}_4 \\ &= 1 \end{aligned}$$

$$\text{as } \gamma^2 = \begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix} = -\hat{1}_2$$

$$\begin{aligned} (\gamma^i)^2 &= \gamma^2 \otimes \sigma_i^2 \\ &= (-\hat{1}_2) \otimes \hat{1}_2 \\ &= -\hat{1}_4 \\ &= -1 \end{aligned}$$

$$\text{as } \sigma_1 \gamma = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} = \begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix} = -\sigma_3$$

$$\begin{aligned} \gamma^0 \gamma^i &= \sigma_1 \gamma \otimes \mathbf{1}_2 \sigma_i \\ &= (-\sigma_3) \otimes \sigma_i \\ \gamma^i \gamma^0 &= \gamma \sigma_1 \otimes \sigma_i \mathbf{1}_2 \\ &= \sigma_3 \otimes \sigma_i \end{aligned}$$

$$\text{as } \gamma^0 \sigma_1 = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} = \sigma_3 \text{ Thus } \gamma^0 \gamma^i + \gamma^i \gamma^0 = 0$$

$$\begin{aligned} \gamma^i \gamma^j &= \gamma^2 \otimes \sigma_i \sigma_j \\ \gamma^j \gamma^i &= \gamma^2 \otimes \sigma_j \sigma_i = \gamma^2 \otimes (-\sigma_i \sigma_j) \end{aligned}$$

as  $\sigma_i \sigma_j + \sigma_j \sigma_i = 0$ . Thus,  $\gamma^i \gamma^j + \gamma^j \gamma^i = 0$  if  $j \neq i$

### 2.2.50

Show that the Dirac equation separates into independent  $2 \times 2$  blocks in the Weyl representation (see Exercise 2.2 .49 ) in the limit that the mass  $m$  approaches zero. This observation is important in the ultra relativistic regime where the rest mass is inconsequential, or for particles of negligible mass (e.g., neutrinos).

**Solution** In the Weyl representation, the matrices  $\gamma^0, \alpha_i$  and the wave function  $\psi$  written as  $2 \times 2$  blocks take the forms

$$\gamma^0 = \begin{bmatrix} 0 & \hat{1}_2 \\ \hat{1}_2 & 0 \end{bmatrix}, \quad \alpha_i = \begin{bmatrix} -\sigma_i & 0 \\ 0 & \sigma_i \end{bmatrix} \quad \text{and} \quad \psi = \begin{bmatrix} \psi_1 \\ \psi_2 \end{bmatrix}$$

In block form  $[\gamma^0 m c^2 + \alpha \cdot p] \psi = E \psi$  becomes

$$\left[ \begin{bmatrix} 0 & m c^2 \\ m c^2 & 0 \end{bmatrix} + \begin{bmatrix} -\sigma \cdot p & 0 \\ 0 & \sigma \cdot p \end{bmatrix} \right] \begin{bmatrix} \psi_1 \\ \psi_2 \end{bmatrix} = E \begin{bmatrix} \psi_1 \\ \psi_2 \end{bmatrix}$$

If  $m$  is zero, this matrix equation becomes two independent equations, one for  $\psi_1$ , and one for  $\psi_2$ . In this limit, one set of solutions will be with  $\psi_2 = 0$  and  $\psi_1$  a solution to  $-\sigma \cdot p \psi_1 = E \psi_1$  and a second set of solutions will have  $\psi_1 = 0$  and a set of  $\psi_2$  identical to the previously found set of  $\psi_1$  but with values of  $E$  of the opposite sign.

### 2.2.51

- (a) Given  $\mathbf{r}' = \mathbf{U}\mathbf{r}$ , with  $\mathbf{U}$  a unitary matrix and  $\mathbf{r}$  a (column) vector with complex elements, show that the magnitude of  $\mathbf{r}$  is invariant under this operation.
- (b) The matrix  $\mathbf{U}$  transforms any column vector  $\mathbf{r}$  with complex elements into  $\mathbf{r}'$ , leaving the magnitude invariant:  $\mathbf{r}^\dagger \mathbf{r} = \mathbf{r}'^\dagger \mathbf{r}'$ . Show that  $\mathbf{U}$  is unitary.

**Solution** For (a) We show that the magnitude of  $r$  is invariant i.e.  $\mathbf{r}'^\dagger \mathbf{r}' = \mathbf{r}^\dagger \mathbf{r}$ . Consider  $\mathbf{r}'^\dagger \mathbf{r}' = (\mathbf{U}\mathbf{r})^\dagger \mathbf{U}\mathbf{r}$

$$\begin{aligned} &= \mathbf{r}^\dagger \mathbf{U}^\dagger \mathbf{U} \mathbf{r} \\ &= \mathbf{r}^\dagger \mathbf{1} \mathbf{r} \\ &= \mathbf{r}^\dagger \mathbf{r} \end{aligned}$$

This shows that the magnitude of  $r$  is invariant under this operation.

**Solution** For (b) all  $r$ ,  $\mathbf{r}'^\dagger \mathbf{r}' = \mathbf{r}^\dagger \mathbf{r}$

$$\begin{aligned} (\mathbf{U}\mathbf{r})^\dagger \mathbf{U}\mathbf{r} &= \mathbf{r}^\dagger \mathbf{r} \\ \mathbf{r}^\dagger \mathbf{U}^\dagger \mathbf{U} \mathbf{r} &= \mathbf{r}^\dagger \mathbf{1} \mathbf{r} \\ \mathbf{U}^\dagger \mathbf{U} &= \mathbf{1} \end{aligned}$$

This shows that  $U$  is unitary.

### 3.2.1

If  $\mathbf{P} = \hat{\mathbf{e}}_x P_x + \hat{\mathbf{e}}_y P_y$  and  $\mathbf{Q} = \hat{\mathbf{e}}_x Q_x + \hat{\mathbf{e}}_y Q_y$  are any two nonparallel (Also nonantiparalleltors in the  $xy$ -plane, show that  $\mathbf{P} \times \mathbf{Q}$  is in the  $z$ -direction.

**Solution** We write the  $P$  and  $Q$  vectors as

$$\mathbf{P} = \langle P_x, P_y, 0 \rangle \quad \mathbf{Q} = \langle Q_x, Q_y, 0 \rangle$$

So

$$\mathbf{P} \times \mathbf{Q} = \begin{vmatrix} \hat{\mathbf{e}}_x & \hat{\mathbf{e}}_y & \hat{\mathbf{e}}_z \\ P_x & P_y & 0 \\ Q_x & Q_y & 0 \end{vmatrix} = (P_x Q_y - Q_x P_y) \hat{\mathbf{e}}_z$$

### 3.2.2

Prove that  $(\mathbf{A} \times \mathbf{B}) \cdot (\mathbf{A} \times \mathbf{B}) = (\mathbf{A}\mathbf{B})^2 - (\mathbf{A} \cdot \mathbf{B})^2$

**Solution**

$$(\mathbf{A} \times \mathbf{B})^2 = (|\mathbf{A}||\mathbf{B}| \sin \theta)^2$$

$$(\mathbf{A} \times \mathbf{B})^2 = \mathbf{A}^2 \times \mathbf{B}^2 \times \sin^2 \theta$$

$$(\mathbf{A} \times \mathbf{B})^2 = \mathbf{A}^2 \times \mathbf{B}^2 \times (1 - \cos^2 \theta)$$

$$(\mathbf{A} \times \mathbf{B})^2 = \mathbf{A}^2 \times \mathbf{B}^2 - \mathbf{A}^2 \times \mathbf{B}^2 \times (\cos^2 \theta)$$

$$(\mathbf{A} \times \mathbf{B})^2 = \mathbf{A}^2 \mathbf{B}^2 - (\mathbf{A} \cdot \mathbf{B})^2$$

### 3.2.3

Using the vectors

$$\mathbf{P} = \hat{\mathbf{e}}_x \cos \theta + \hat{\mathbf{e}}_y \sin \theta$$

$$\mathbf{Q} = \hat{\mathbf{e}}_x \cos \varphi - \hat{\mathbf{e}}_y \sin \varphi$$

$$\mathbf{R} = \hat{\mathbf{e}}_x \cos \varphi + \hat{\mathbf{e}}_y \sin \varphi$$

prove the familiar trigonometric identities

$$\sin(\theta + \varphi) = \sin \theta \cos \varphi + \cos \theta \sin \varphi$$

$$\cos(\theta + \varphi) = \cos \theta \cos \varphi - \sin \theta \sin \varphi$$

**Solution** Consider  $\mathbf{P} \cdot \mathbf{Q}$  as

$$\mathbf{P} \cdot \mathbf{Q} = (\hat{x} \cos \theta + \hat{y} \sin \theta) \cdot (\hat{x} \cos \varphi - \hat{y} \sin \varphi) + \hat{y} \sin \theta \hat{x} \cos \varphi - \hat{y} \sin \theta \sin \varphi$$

$$\mathbf{P} \cdot \mathbf{Q} = (1 \times \cos \theta \cos \varphi) - (0 \times \cos \theta \sin \varphi) + (0 \times \sin \theta \cos \varphi) - (1 \times \sin \theta \sin \varphi)$$

$$\mathbf{P} \cdot \mathbf{Q} = \cos \theta \cos \varphi - \sin \theta \sin \varphi$$

And by the product rule,  $\mathbf{P} \cdot \mathbf{Q} = \cos(\theta + \varphi)$

$$\cos(\theta + \varphi) = \cos \theta \cos \varphi - \sin \theta \sin \varphi$$

## 3.2.4

(a) Find a vector  $\mathbf{A}$  that is perpendicular to

$$\mathbf{U} = 2\hat{\mathbf{e}}_x + \hat{\mathbf{e}}_y - \hat{\mathbf{e}}_z$$

$$\mathbf{V} = \hat{\mathbf{e}}_x - \hat{\mathbf{e}}_y + \hat{\mathbf{e}}_z$$

(b) What is  $\mathbf{A}$  if, in addition to this requirement, we demand that it have unit magnitude?

**Solution** For (a) we have  $\mathbf{U} = 2\hat{\mathbf{e}}_x + \hat{\mathbf{e}}_y - \hat{\mathbf{e}}_z$ ,  $\mathbf{V} = \hat{\mathbf{e}}_x - \hat{\mathbf{e}}_y + \hat{\mathbf{e}}_z$

$$\mathbf{U} \times \mathbf{V} = \begin{vmatrix} \hat{\mathbf{e}}_x & \hat{\mathbf{e}}_y & \hat{\mathbf{e}}_z \\ 2 & 1 & -1 \\ 1 & -1 & 1 \end{vmatrix} = \hat{\mathbf{e}}_x(1-1) - \hat{\mathbf{e}}_y(2+1) + \hat{\mathbf{e}}_z(-2-1)$$

$$\mathbf{U} \times \mathbf{V} = -\hat{\mathbf{e}}_y(3) + \hat{\mathbf{e}}_z(-3) = -3\hat{\mathbf{e}}_y - 3\hat{\mathbf{e}}_z$$

**Solution** For (b) We know  $\mathbf{A}$  is  $-3\hat{\mathbf{e}}_y - 3\hat{\mathbf{e}}_z$ , so the magnitude of  $\mathbf{A}$  is

$$|\mathbf{A}| = \sqrt{3^2 + 3^2} = \sqrt{18} = 3\sqrt{2}$$

From this

$$\mathbf{A} = \frac{-3\hat{\mathbf{e}}_y - 3\hat{\mathbf{e}}_z}{3\sqrt{2}} = \frac{-\hat{\mathbf{e}}_y - \hat{\mathbf{e}}_z}{\sqrt{2}}$$

## 3.2.5

If four vectors  $\mathbf{a}$ ,  $\mathbf{b}$ ,  $\mathbf{c}$ , and  $\mathbf{d}$  all lie in the same plane, show that

$$(\mathbf{a} \times \mathbf{b}) \times (\mathbf{c} \times \mathbf{d}) = 0$$

Hint. Consider the directions of the cross-product vectors.

**Solution** Since all four vectors lie in the same plane, the cross product of any two of them would be orthogonal to the plane. Thus:

$$\mathbf{v}_1 = (\mathbf{a} \times \mathbf{b})$$

$$\mathbf{v}_2 = (\mathbf{c} \times \mathbf{d})$$

By definition,  $\mathbf{v}_1$  and  $\mathbf{v}_2$  are parallel, so  $\mathbf{v}_1 \times \mathbf{v}_2 = 0$

## 3.2.6

Derive the law of sines (see Fig. 3.4) :

$$\frac{\sin \alpha}{|A|} = \frac{\sin \beta}{|B|} = \frac{\sin \gamma}{|C|}$$

**Solution** We have  $\mathbf{A} - \mathbf{B} - \mathbf{C} = 0$  so we cross both sides by  $\mathbf{A}$

$$\mathbf{A} \times \mathbf{A} - \mathbf{A} \times \mathbf{B} - \mathbf{A} \times \mathbf{C} = \mathbf{A} \times 0$$

$$0 - \mathbf{A} \times \mathbf{B} - \mathbf{A} \times \mathbf{C} = 0$$

$$-\mathbf{A} \times \mathbf{B} - \mathbf{A} \times \mathbf{C} = 0$$

$$-\mathbf{A} \times \mathbf{C} = \mathbf{A} \times \mathbf{B}$$



$$\mathbf{C} \times \mathbf{A} = \mathbf{A} \times \mathbf{B}$$

$$|\mathbf{C}||\mathbf{A}| \sin \beta = |\mathbf{A}||\mathbf{B}| \sin \gamma$$

Again, we cross both sides of  $\mathbf{A} - \mathbf{B} - \mathbf{C} = 0$  by  $\mathbf{B}$

$$\mathbf{B} \times \mathbf{A} - \mathbf{B} \times \mathbf{B} - \mathbf{B} \times \mathbf{C} = \mathbf{B} \times 0$$

$$\mathbf{B} \times \mathbf{A} - \mathbf{B} \times \mathbf{C} = 0$$

$$\mathbf{B} \times \mathbf{A} = \mathbf{B} \times \mathbf{C}$$

$$|\mathbf{B}||\mathbf{A}| \sin \gamma = |\mathbf{B}||\mathbf{C}| \sin \alpha$$

$$|\mathbf{A}| \sin \gamma = |\mathbf{C}| \sin \alpha$$

$$\frac{\sin \gamma}{|\mathbf{C}|} = \frac{\sin \alpha}{|\mathbf{A}|}$$

### 3.2.7

The magnetic induction  $\mathbf{B}$  is defined by the Lorentz force equation,

$$\mathbf{F} = q(\mathbf{v} \times \mathbf{B})$$

Carrying out three experiments, we find that if

$$\mathbf{v} = \hat{\mathbf{e}}_x, \quad \frac{\mathbf{F}}{q} = 2\hat{\mathbf{e}}_z - 4\hat{\mathbf{e}}_y$$

$$\mathbf{v} = \hat{\mathbf{e}}_y, \quad \frac{\mathbf{F}}{q} = 4\hat{\mathbf{e}}_x - \hat{\mathbf{e}}_z$$

$$\mathbf{v} = \hat{\mathbf{e}}_z, \quad \frac{\mathbf{F}}{q} = \hat{\mathbf{e}}_y - 2\hat{\mathbf{e}}_x$$

From the results of these three separate experiments calculate the magnetic induction  $\mathbf{B}$ .

**Solution** From the first condition  $\mathbf{v} = \hat{\mathbf{e}}_x, \frac{\mathbf{F}}{q} = 2\hat{\mathbf{e}}_z - 4\hat{\mathbf{e}}_y$

$$\mathbf{v} \times \mathbf{B} = \begin{vmatrix} \hat{\mathbf{e}}_x & \hat{\mathbf{e}}_y & \hat{\mathbf{e}}_z \\ 1 & 0 & 0 \\ B_x & B_y & B_z \end{vmatrix} = \hat{\mathbf{e}}_x(0) - \hat{\mathbf{e}}_y(B_z) + \hat{\mathbf{e}}_z(B_y) = -\hat{\mathbf{e}}_y(B_z) + \hat{\mathbf{e}}_z(B_y)$$

$$\frac{\mathbf{F}}{q} = 2\hat{\mathbf{e}}_z - 4\hat{\mathbf{e}}_y,$$

$$\mathbf{v} \times \mathbf{B} = -\hat{\mathbf{e}}_y(B_z) + \hat{\mathbf{e}}_z(B_y)$$

$$B_z = 4, B_y = 2$$

Now, from the second condition  $\mathbf{v} = \hat{\mathbf{e}}_y, \frac{\mathbf{F}}{q} = 4\hat{\mathbf{e}}_x - \hat{\mathbf{e}}_z$

$$\mathbf{v} \times \mathbf{B} = \begin{vmatrix} \hat{\mathbf{e}}_x & \hat{\mathbf{e}}_y & \hat{\mathbf{e}}_z \\ 0 & 1 & 0 \\ B_x & B_y & B_z \end{vmatrix} = \hat{\mathbf{e}}_x(B_z) - \hat{\mathbf{e}}_y(0) - \hat{\mathbf{e}}_z(B_x) = \hat{\mathbf{e}}_x(B_z) - \hat{\mathbf{e}}_z(B_x)$$

$$\frac{\mathbf{F}}{q} = 4\hat{\mathbf{e}}_x - \hat{\mathbf{e}}_z$$

$$\mathbf{v} \times \mathbf{B} = \hat{\mathbf{e}}_x(B_z) - \hat{\mathbf{e}}_z(B_x)$$

$$\mathbf{B}_z = 4, \mathbf{B}_x = 1$$

From the third condition

$$v = \hat{\mathbf{e}}_z$$

$$\frac{\mathbf{F}}{q} = \hat{\mathbf{e}}_y - 2\hat{\mathbf{e}}_x$$

$$\mathbf{v} \times \mathbf{B} = \begin{vmatrix} \hat{\mathbf{e}}_x & \hat{\mathbf{e}}_y & \hat{\mathbf{e}}_z \\ 0 & 0 & 1 \\ \mathbf{B}_x & \mathbf{B}_y & \mathbf{B}_z \end{vmatrix} = \hat{\mathbf{e}}_x(-\mathbf{B}_y) - \hat{\mathbf{e}}_y(-\mathbf{B}_x) - \hat{\mathbf{e}}_z(0) = -\hat{\mathbf{e}}_x(\mathbf{B}_y) + \hat{\mathbf{e}}_y(\mathbf{B}_x)$$

$$\mathbf{v} \times \mathbf{B} = -\hat{\mathbf{e}}_x(\mathbf{B}_y) + \hat{\mathbf{e}}_y(\mathbf{B}_x)$$

$$\frac{\mathbf{F}}{q} = \hat{\mathbf{e}}_y - 2\hat{\mathbf{e}}_x$$

$$\mathbf{B}_y = 2, \mathbf{B}_x = 1$$

### 3.2.8

You are given the three vectors  $\mathbf{A}$ ,  $\mathbf{B}$ , and  $\mathbf{C}$ ,

$$\mathbf{A} = \hat{\mathbf{e}}_x + \hat{\mathbf{e}}_y$$

$$\mathbf{B} = \hat{\mathbf{e}}_y + \hat{\mathbf{e}}_z$$

$$\mathbf{C} = \hat{\mathbf{e}}_x - \hat{\mathbf{e}}_z$$

Therefore, from above three conditions magnetic induction is given by  $\mathbf{B} = \hat{x} + 2\hat{y} + 4\hat{z}$

**Solution** For (a),  $\mathbf{A} \cdot \mathbf{B} \times \mathbf{C} = 0$ . Because  $\mathbf{A}$  is the plane of  $\mathbf{B}$  and  $\mathbf{C}$ . The parallelepiped has zero height above the  $BC$  plane. So therefore volume will be zero. Therefore, the scalar triple product is zero.

**Solution** For (b)

$$(\mathbf{B} \times \mathbf{C}) = \begin{vmatrix} \hat{\mathbf{e}}_x & \hat{\mathbf{e}}_y & \hat{\mathbf{e}}_z \\ 0 & 1 & 1 \\ 1 & 0 & -1 \end{vmatrix} = \hat{\mathbf{e}}_x(-1) - \hat{\mathbf{e}}_y(-1) + \hat{\mathbf{e}}_z(-1) = -\hat{\mathbf{e}}_x + \hat{\mathbf{e}}_y - \hat{\mathbf{e}}_z$$

$$\mathbf{A} \times (\mathbf{B} \times \mathbf{C}) = \begin{vmatrix} \hat{\mathbf{e}}_x & \hat{\mathbf{e}}_y & \hat{\mathbf{e}}_z \\ 1 & 1 & 0 \\ -1 & 1 & -1 \end{vmatrix} = \hat{\mathbf{e}}_x(-1) - \hat{\mathbf{e}}_y(-1) + \hat{\mathbf{e}}_z(1+1) = -\hat{\mathbf{e}}_x + \hat{\mathbf{e}}_y + 2\hat{\mathbf{e}}_z$$

### 3.2.9

Prove Jacobi's identity for vector products:

$$\mathbf{a} \times (\mathbf{b} \times \mathbf{c}) + \mathbf{b} \times (\mathbf{c} \times \mathbf{a}) + \mathbf{c} \times (\mathbf{a} \times \mathbf{b}) = 0$$

**Solution** From  $\mathbf{BAC} - \mathbf{CAB}$  rule  $\mathbf{a} \times (\mathbf{b} \times \mathbf{c}) = b(a \cdot c) - c(a \cdot b)$ . The entire equation can be written as

$$\mathbf{a} \times (\mathbf{b} \times \mathbf{c}) + \mathbf{b} \times (\mathbf{c} \times \mathbf{a}) + \mathbf{c} \times (\mathbf{a} \times \mathbf{b}) = [b(a \cdot c) - c(a \cdot b)] + [(b \cdot a)c - (b \cdot c)a] + [(c \cdot b)a - (c \cdot a)b]$$

since the dot product is commutative so they become zero. Therefore,

$$\mathbf{a} \times (\mathbf{b} \times \mathbf{c}) + \mathbf{b} \times (\mathbf{c} \times \mathbf{a}) + \mathbf{c} \times (\mathbf{a} \times \mathbf{b}) = 0$$

## 3.2.10

A vector  $\mathbf{A}$  is decomposed into a radial vector  $\mathbf{A}_r$  and a tangential vector  $\mathbf{A}_t$ . If  $\hat{\mathbf{r}}$  is a unit vector in the radial direction, show that (a)  $\mathbf{A}_r = \hat{\mathbf{r}}(\mathbf{A} \cdot \hat{\mathbf{r}})$  and (b)  $\mathbf{A}_t = -\hat{\mathbf{r}} \times (\hat{\mathbf{r}} \times \mathbf{A})$

**Solution** Let  $\mathbf{A} = \mathbf{A}_r \hat{\mathbf{r}} + \mathbf{A}_t \hat{\theta}$

$$\mathbf{A} \cdot \hat{\mathbf{r}} = \mathbf{A}_r, \text{ as } \hat{\mathbf{r}} \cdot \hat{\mathbf{r}} = 1$$

The left-hand side is:

$$\mathbf{A}_r = \mathbf{A}_r \hat{\mathbf{r}}$$

since  $\hat{\mathbf{r}}$  is the unit vector. The right-hand side is:

$$\hat{\mathbf{r}}(\mathbf{A} \cdot \hat{\mathbf{r}}) = \hat{\mathbf{r}}(\mathbf{A}_r) = \mathbf{A}_r \hat{\mathbf{r}}$$

For (b), taking dot product of both sides of the equation  $\mathbf{A}_t = -\hat{\mathbf{r}} \times (\hat{\mathbf{r}} \times \mathbf{A})$  by  $\hat{\mathbf{r}}$  we get

$$\mathbf{A}_t \cdot \hat{\mathbf{r}} = [-\hat{\mathbf{r}} \times (\hat{\mathbf{r}} \times \mathbf{A})] \cdot \hat{\mathbf{r}}$$

The left-hand side is:

$$\mathbf{A}_t \cdot \hat{\mathbf{r}} = \mathbf{A}_t \hat{\theta} \cdot \hat{\mathbf{r}} = 0$$

$$\begin{aligned} [-\hat{\mathbf{r}} \times (\hat{\mathbf{r}} \times \mathbf{A})] \cdot \hat{\mathbf{r}} &= [\hat{\mathbf{r}} \times (\mathbf{A} \times \hat{\mathbf{r}})] \cdot \hat{\mathbf{r}} \\ &= [\mathbf{A}(\hat{\mathbf{r}} \cdot \hat{\mathbf{r}}) - \hat{\mathbf{r}}(\mathbf{A} \cdot \hat{\mathbf{r}})] \cdot \hat{\mathbf{r}} \\ &= [\mathbf{A} - \hat{\mathbf{r}}\mathbf{A}_r] \cdot \hat{\mathbf{r}} \\ &= \mathbf{A} \cdot \hat{\mathbf{r}} - \mathbf{A}_r \hat{\mathbf{r}} \cdot \hat{\mathbf{r}} \\ &= \mathbf{A}_r - \mathbf{A}_r \\ &= 0 \end{aligned}$$

## 3.2.11

Prove that a necessary and sufficient condition for the three (nonvanishing) vectors  $\mathbf{A}$ ,  $\mathbf{B}$ , and  $\mathbf{C}$  to be coplanar is the vanishing of the scalar triple product

$$\mathbf{A} \cdot \mathbf{B} \times \mathbf{C} = 0$$

**Solution** It should be kept in mind that scalar triple product can also be represented as the volume of parallelepiped which is formed by three vectors. So we can say that if scalar triple product is equal to zero then vectors are coplanar as the parallelepipeds have no volume.

## 3.2.12

Three vectors  $\mathbf{A}$ ,  $\mathbf{B}$ , and  $\mathbf{C}$  are given by

$$\begin{aligned} \mathbf{A} &= 3\hat{\mathbf{e}}_x - 2\hat{\mathbf{e}}_y + 2\hat{\mathbf{z}} \\ \mathbf{B} &= 6\hat{\mathbf{e}}_x + 4\hat{\mathbf{e}}_y - 2\hat{\mathbf{z}} \\ \mathbf{C} &= -3\hat{\mathbf{e}}_x - 2\hat{\mathbf{e}}_y - 4\hat{\mathbf{z}} \end{aligned}$$

Compute the values of  $\mathbf{A} \cdot \mathbf{B} \times \mathbf{C}$  and  $\mathbf{A} \times (\mathbf{B} \times \mathbf{C})$ ,  $\mathbf{C} \times (\mathbf{A} \times \mathbf{B})$  and  $\mathbf{B} \times (\mathbf{C} \times \mathbf{A})$

**Solution** First we can find  $\mathbf{B} \times \mathbf{C}$  and then can perform dot product

$$\mathbf{B} \times \mathbf{C} = \begin{vmatrix} \hat{x} & \hat{y} & \hat{z} \\ 6 & 4 & -2 \\ -3 & -2 & -4 \end{vmatrix} = \hat{x}(-16-4) - \hat{y}(-24-6) + \hat{z}(-12+12) = -20\hat{x} + 30\hat{y}$$

$$\mathbf{A} \cdot (\mathbf{B} \times \mathbf{C}) = (3\hat{x} - 2\hat{y} + 2\hat{z}) \cdot (-20\hat{x} + 30\hat{y}) = -60 - 60 = -120$$

With this,  $\mathbf{A} \cdot (\mathbf{B} \times \mathbf{C}) = -120$

**Solution** For (b) we have that the vector  $\mathbf{A}$

$$\mathbf{A} = (3\hat{x} - 2\hat{y} + 2\hat{z})$$

$$\mathbf{A} \times (\mathbf{B} \times \mathbf{C}) = \begin{vmatrix} \hat{x} & \hat{y} & \hat{z} \\ 3 & -2 & 2 \\ -20 & 30 & 0 \end{vmatrix} = \hat{x}(-60) - \hat{y}(40) + \hat{z}(50)$$

With this,

$$\mathbf{A} \times (\mathbf{B} \times \mathbf{C}) = (-60)\hat{x} - (40)\hat{y} + (50)\hat{z}$$

**Solution** For (c)

$$(\mathbf{A} \times \mathbf{B}) = \begin{vmatrix} \hat{x} & \hat{y} & \hat{z} \\ 3 & -2 & 2 \\ 6 & 4 & -2 \end{vmatrix} = \hat{x}(-4) - \hat{y}(-18) + \hat{z}(24)$$

$$\mathbf{C} \times (\mathbf{A} \times \mathbf{B}) = \begin{vmatrix} \hat{x} & \hat{y} & \hat{z} \\ -3 & -2 & -4 \\ -4 & 18 & 24 \end{vmatrix} = \hat{x}(26) - \hat{y}(-88) + \hat{z}(-62)$$

**Solution** For (d)

$$(\mathbf{C} \times \mathbf{A}) = \begin{vmatrix} \hat{x} & \hat{y} & \hat{z} \\ -3 & -2 & -4 \\ 3 & -2 & 2 \end{vmatrix} = \hat{x}(-12) - \hat{y}(6) + \hat{z}(12)$$

$$\mathbf{B} \times (\mathbf{C} \times \mathbf{A}) = \begin{vmatrix} \hat{x} & \hat{y} & \hat{z} \\ 6 & 4 & -2 \\ -12 & -6 & 12 \end{vmatrix} = \hat{x}(36) - \hat{y}(48) + \hat{z}(12)$$

### 3.2.13

Show that

$$(\mathbf{A} \times \mathbf{B}) \cdot (\mathbf{C} \times \mathbf{D}) = (\mathbf{A} \cdot \mathbf{C})(\mathbf{B} \cdot \mathbf{D}) - (\mathbf{A} \cdot \mathbf{D})(\mathbf{B} \cdot \mathbf{C})$$

**Solution** Let  $\mathbf{C} \times \mathbf{D} = m$ . Now, consider the scalar triple product  $(\mathbf{A} \times \mathbf{B}) \cdot m$ . since cross and dot product can be interchanged, we have,

$$(\mathbf{A} \times \mathbf{B}) \cdot m = \mathbf{A} \cdot (\mathbf{B} \times m)$$

Resubstituting  $m$  we get

$$\begin{aligned} (\mathbf{A} \times \mathbf{B}) \cdot (\mathbf{C} \times \mathbf{D}) &= \mathbf{A} \cdot [\mathbf{B} \times (\mathbf{C} \times \mathbf{D})] \\ &= \mathbf{A} \cdot [(\mathbf{B} \cdot \mathbf{D})\mathbf{C} - (\mathbf{B} \cdot \mathbf{C})\mathbf{D}] \\ &= (\mathbf{A} \cdot \mathbf{C})(\mathbf{B} \cdot \mathbf{D}) - (\mathbf{A} \cdot \mathbf{D})(\mathbf{B} \cdot \mathbf{C}) \end{aligned}$$

Thus,  $(\mathbf{A} \times \mathbf{B}) \cdot (\mathbf{C} \times \mathbf{D}) = (\mathbf{A} \cdot \mathbf{C})(\mathbf{B} \cdot \mathbf{D}) - (\mathbf{A} \cdot \mathbf{D})(\mathbf{B} \cdot \mathbf{C})$

## 3.2.14

Show that  $(\mathbf{A} \times \mathbf{B}) \times (\mathbf{C} \times \mathbf{D}) = (\mathbf{A} \cdot \mathbf{B} \times \mathbf{D})\mathbf{C} - (\mathbf{A} \cdot \mathbf{B} \times \mathbf{C})\mathbf{D}$

**Solution** Let  $\mathbf{A} \times \mathbf{B} = \mathbf{m}$

$$\begin{aligned} (\mathbf{A} \times \mathbf{B}) \times (\mathbf{C} \times \mathbf{D}) &= \mathbf{m} \times (\mathbf{C} \times \mathbf{D}) \\ &= (\mathbf{m} \cdot \mathbf{D})\mathbf{C} - (\mathbf{m} \cdot \mathbf{C})\mathbf{D} \\ &= ((\mathbf{A} \times \mathbf{B}) \cdot \mathbf{D})\mathbf{C} - ((\mathbf{A} \times \mathbf{B}) \cdot \mathbf{C})\mathbf{D} \\ &= (\mathbf{A} \cdot (\mathbf{B} \times \mathbf{D}))\mathbf{C} - (\mathbf{A} \cdot (\mathbf{B} \times \mathbf{C}))\mathbf{D} \end{aligned}$$

## 3.2.15

An electric charge  $q_1$  moving with velocity  $\mathbf{v}_1$  produces a magnetic induction  $\mathbf{B}$  given by

$$\mathbf{B} = \frac{\mu_0}{4\pi} q_1 \frac{\mathbf{v}_1 \times \hat{\mathbf{r}}}{r^2} \quad (\text{mks units}),$$

where  $\hat{\mathbf{r}}$  is a unit vector that points from  $q_1$  to the point at which  $\mathbf{B}$  is measured (Biot and Savart law).

- (a) Show that the magnetic force exerted by  $q_1$  on a second charge  $q_2$ , velocity  $\mathbf{v}_2$ , is given by the vector triple product

$$\mathbf{F}_2 = \frac{\mu_0}{4\pi} \frac{q_1 q_2}{r^2} \mathbf{v}_2 \times (\mathbf{v}_1 \times \hat{\mathbf{r}})$$

- (b) Write out the corresponding magnetic force  $\mathbf{F}_1$  that  $q_2$  exerts on  $q_1$ . Define your unit radial vector. How do  $\mathbf{F}_1$  and  $\mathbf{F}_2$  compare?
- (c) Calculate  $\mathbf{F}_1$  and  $\mathbf{F}_2$  for the case of  $q_1$  and  $q_2$  moving along parallel trajectories side by side.

**Solution** For (a) The magnetic force  $\mathbf{F}_2$  is defined by the Lorentz force equation,

$$\begin{aligned} \mathbf{F}_2 &= q_2 (\mathbf{v}_2 \times \mathbf{B}_1) \\ &= \frac{\mu_0}{4\pi} q_1 q_2 \frac{\mathbf{v}_2 \times (\mathbf{v}_1 \times \hat{\mathbf{r}})}{r^2} \end{aligned}$$

and

$$\mathbf{B}_1 = \frac{\mu_0}{4\pi} q_1 \frac{\mathbf{v}_1 \times \hat{\mathbf{r}}}{r^2}$$

For (b) The magnetic force  $\mathbf{F}_1$  is defined by the Lorentz force equation,

$$\begin{aligned} \mathbf{F}_1 &= q_1 (\mathbf{v}_1 \times \mathbf{B}_2) \\ &= -\frac{\mu_0}{4\pi} q_1 q_2 \frac{\mathbf{v}_1 \times (\mathbf{v}_2 \times \hat{\mathbf{r}})}{r^2} \end{aligned}$$

and

$$\mathbf{B}_2 = \frac{\mu_0}{4\pi} q_2 \frac{\mathbf{v}_2 \times (-\hat{\mathbf{r}})}{r^2}$$

From part we have,

$$\mathbf{F}_2 = \frac{\mu_0}{4\pi} q_1 q_2 \frac{\mathbf{v}_2 \times (\mathbf{v}_1 \times \hat{\mathbf{r}})}{r^2}$$

since  $-\mathbf{v}_1 \times (\mathbf{v}_2 \times \hat{\mathbf{r}}) \neq \mathbf{v}_2 \times (\mathbf{v}_1 \times \hat{\mathbf{r}})$ ,  $\mathbf{F}_1 \neq \mathbf{F}_2$  For (c) we have that

$$\begin{aligned}\mathbf{F}_1 &= -\frac{\mu_0}{4\pi} q_1 q_2 \frac{\mathbf{v} \times (\mathbf{v} \times \hat{\mathbf{r}})}{r^2} \\ &= -\frac{\mu_0}{4\pi} q_1 q_2 \frac{\mathbf{v}(\mathbf{v} \cdot \hat{\mathbf{r}}) - \hat{\mathbf{r}}(\mathbf{v} \cdot \mathbf{v})}{r^2} \\ &= -\frac{\mu_0}{4\pi} q_1 q_2 \frac{0 - \hat{\mathbf{r}}(\mathbf{v} \cdot \mathbf{v})}{r^2} \\ &= \frac{\mu_0}{4\pi} q_1 q_2 \frac{\mathbf{v}^2 \hat{\mathbf{r}}}{r^2}\end{aligned}$$

and

$$\begin{aligned}\mathbf{F}_2 &= \frac{\mu_0}{4\pi} q_1 q_2 \frac{\mathbf{v} \times (\mathbf{v} \times \hat{\mathbf{r}})}{r^2} \\ &= \frac{\mu_0}{4\pi} q_1 q_2 \frac{\mathbf{v}(\mathbf{v} \cdot \hat{\mathbf{r}}) - \hat{\mathbf{r}}(\mathbf{v} \cdot \mathbf{v})}{r^2} \\ &= \frac{\mu_0}{4\pi} q_1 q_2 \frac{0 - \hat{\mathbf{r}}(\mathbf{v} \cdot \mathbf{v})}{r^2} \\ &= -\frac{\mu_0}{4\pi} q_1 q_2 \frac{\mathbf{v}^2 \hat{\mathbf{r}}}{r^2}\end{aligned}$$

Thus,  $\mathbf{F}_1 = -\mathbf{F}_2$

## Chapter 3.3

**3.3.1** A rotation  $\varphi_1 + \varphi_2$  about the  $z$ -axis is carried out as two successive rotations  $\varphi_1$  and  $\varphi_2$ , each about the  $z$ -axis. Use the matrix representation of the rotations to derive the trigonometric identities

**Solution**

$$\begin{aligned}\cos(\varphi_1 + \varphi_2) &= \cos \varphi_1 \cos \varphi_2 - \sin \varphi_1 \sin \varphi_2 \\ \sin(\varphi_1 + \varphi_2) &= \sin \varphi_1 \cos \varphi_2 + \cos \varphi_1 \sin \varphi_2 \\ \begin{bmatrix} \cos(\varphi_1 + \varphi_2) & \sin(\varphi_1 + \varphi_2) \\ -\sin(\varphi_1 + \varphi_2) & \cos(\varphi_1 + \varphi_2) \end{bmatrix} &= \begin{bmatrix} \cos \varphi_2 & \sin \varphi_2 \\ -\sin \varphi_2 & \cos \varphi_2 \end{bmatrix} \begin{bmatrix} \cos \varphi_1 & \sin \varphi_1 \\ -\sin \varphi_1 & \cos \varphi_1 \end{bmatrix} \\ &= \begin{bmatrix} \cos \varphi_1 \cos \varphi_2 - \sin \varphi_1 \sin \varphi_2 & \sin \varphi_1 \cos \varphi_2 + \cos \varphi_1 \sin \varphi_2 \\ -\cos \varphi_1 \sin \varphi_2 - \sin \varphi_1 \cos \varphi_2 & -\sin \varphi_1 \sin \varphi_2 + \cos \varphi_1 \cos \varphi_2 \end{bmatrix}\end{aligned}$$

**3.3.2** A corner reflector is formed by three mutually perpendicular reflecting surfaces. Show that a ray of light incident upon the corner (striking all three surfaces) is reflected back along a line parallel to the line of incidence. Hint. Consider the effect of a reflection on the components of a vector describing the direction of the light ray.

**Solution** Here we are asked to prove that the ray of light incident upon the corner reflector is reflected back along a line parallel to the line of incidence.

So for this align the reflecting surfaces with  $xy$ ,  $xz$ , and  $yz$  planes. If an incoming ray strikes the  $xy$  plane, the  $z$  component of its direction of propagation is reversed. A strike on the  $xz$  plane reverses its  $y$  component, and a strike on the  $yz$  plane reverses its  $x$  component.

**3.3.3** Let  $x$  and  $y$  be column vectors. Under an orthogonal transformation  $S$ , they become  $x' = Sx$  and  $y' = Sy$ . Show that  $(x')^T y' = x^T y$ , a result equivalent to the invariance of the dot product under a rotational transformation.

**Solution** It is given that  $S$  is orthogonal, if so its transpose is also its inverse. From this

$$(x')^T = (Sx)^T = x^T S^T = x^T S^{-1}$$

Then

$$(x')^T y' = x^T S^{-1} Sy = x^T y$$

Therefore  $(x')^T y' = x^T y$

**3.3.4** Given the orthogonal transformation matrix  $S$  and vectors  $\mathbf{a}$  and  $\mathbf{b}$ ,

$$S = \begin{bmatrix} 0.80 & 0.60 & 0.00 \\ -0.48 & 0.64 & 0.60 \\ 0.36 & -0.48 & 0.80 \end{bmatrix}, \quad \mathbf{a} = \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix}, \quad \mathbf{b} = \begin{bmatrix} 0 \\ 2 \\ -1 \end{bmatrix}$$

(a) Calculate  $\det(S)$ .

(b) Verify that  $\mathbf{a} \cdot \mathbf{b}$  is invariant under application of  $S$  to  $\mathbf{a}$  and  $\mathbf{b}$ .

(c) Determine what happens to  $\mathbf{a} \times \mathbf{b}$  under application of  $S$  to  $\mathbf{a}$  and  $\mathbf{b}$ . Is this what is expected?

**Solution** For (a) given

$$S = \begin{bmatrix} 0.80 & 0.60 & 0.00 \\ -0.48 & 0.64 & 0.60 \\ 0.36 & -0.48 & 0.80 \end{bmatrix}$$

$$\det(S) = \det \begin{bmatrix} 0.80 & 0.60 & 0.00 \\ -0.48 & 0.64 & 0.60 \\ 0.36 & -0.48 & 0.80 \end{bmatrix} = 1$$

**Solution** For (b) we show that  $a \cdot b$  is invariant under application of  $S$  to  $a$  and  $b$ .

$$\mathbf{a}' = S\mathbf{a}$$

$$= \begin{bmatrix} 0.80 & 0.60 & 0.00 \\ -0.48 & 0.64 & 0.60 \\ 0.36 & -0.48 & 0.80 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix} \\ = \begin{bmatrix} 0.80 \\ 0.12 \\ 1.16 \end{bmatrix}$$

$$\mathbf{b}' = S\mathbf{b}$$

$$= \begin{bmatrix} 0.80 & 0.60 & 0.00 \\ -0.48 & 0.64 & 0.60 \\ 0.36 & -0.48 & 0.80 \end{bmatrix} \begin{bmatrix} 0 \\ 2 \\ -1 \end{bmatrix} \\ = \begin{bmatrix} 1.20 \\ 0.68 \\ -1.76 \end{bmatrix}$$

$$a \cdot b = \begin{bmatrix} 1 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 0 \\ 2 \\ -1 \end{bmatrix} = -1$$

$$a' \cdot b' = \begin{bmatrix} 0.80 & 0.12 & 1.16 \end{bmatrix} \begin{bmatrix} 1.20 \\ 0.68 \\ -1.76 \end{bmatrix} = -1$$

Thus,  $a \cdot b$  is invariant under application of  $S$  to  $a$  and  $b$ .

**Solution** For (c) we find  $\mathbf{a} \times \mathbf{b}$

$$\mathbf{a} \times \mathbf{b} = \begin{vmatrix} i & j & k \\ 1 & 0 & 1 \\ 0 & 2 & -1 \end{vmatrix} = \begin{bmatrix} -2 \\ 1 \\ 2 \end{bmatrix}$$

$$S(\mathbf{a} \times \mathbf{b}) = \begin{bmatrix} 0.80 & 0.60 & 0.00 \\ -0.48 & 0.64 & 0.60 \\ 0.36 & -0.48 & 0.80 \end{bmatrix} \begin{bmatrix} -2 \\ 1 \\ 2 \end{bmatrix} \\ = \begin{bmatrix} -1 \\ 2.8 \\ 0.4 \end{bmatrix}$$

$$\mathbf{a}' \times \mathbf{b}' = \begin{vmatrix} i & j & k \\ 0.80 & 0.12 & 1.16 \\ 1.20 & 0.68 & -1.76 \end{vmatrix} = \begin{bmatrix} -1 \\ 2.8 \\ 0.4 \end{bmatrix}$$

Thus,  $S(\mathbf{a} \times \mathbf{b}) = \mathbf{a}' \times \mathbf{b}'$  and hence  $\mathbf{a} \times \mathbf{b}$  is a vector.

**3.3.5** Using  $\mathbf{a}$  and  $\mathbf{b}$  as defined in Exercise 3.3.5 but with



$$S = \begin{bmatrix} 0.60 & 0.00 & 0.80 \\ -0.64 & -0.60 & 0.48 \\ -0.48 & 0.80 & 0.36 \end{bmatrix} \quad \text{and} \quad \mathbf{c} = \begin{bmatrix} 2 \\ 1 \\ 3 \end{bmatrix}$$

(a) Calculate  $\det(S)$ .

(b)  $\mathbf{a} \times \mathbf{b}$

(c)  $(\mathbf{a} \times \mathbf{b}) \cdot \mathbf{c}$

(d)  $\mathbf{a} \times (\mathbf{b} \times \mathbf{c})$

**Solution** For (a) Given that

$$S = \begin{bmatrix} 0.60 & 0.00 & 0.80 \\ -0.64 & -0.60 & 0.48 \\ -0.48 & 0.80 & 0.36 \end{bmatrix}$$

Then

$$\det(S) = \det \begin{bmatrix} 0.60 & 0.00 & 0.80 \\ -0.64 & -0.60 & 0.48 \\ -0.48 & 0.80 & 0.36 \end{bmatrix} = 1$$

Apply  $\mathbf{S}$  to  $\mathbf{a}$ ,  $\mathbf{b}$ , and  $\mathbf{c}$ .

$$\mathbf{a}' = \mathbf{S}\mathbf{a}$$

$$\begin{aligned} &= \begin{bmatrix} 0.60 & 0.00 & 0.80 \\ -0.64 & -0.60 & 0.48 \\ -0.48 & 0.80 & 0.36 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix} \\ &= \begin{bmatrix} 1.40 \\ -0.16 \\ -0.12 \end{bmatrix} \end{aligned}$$

$$\mathbf{b}' = \mathbf{S}\mathbf{b}$$

$$\begin{aligned} &= \begin{bmatrix} 0.60 & 0.00 & 0.80 \\ -0.64 & -0.60 & 0.48 \\ -0.48 & 0.80 & 0.36 \end{bmatrix} \begin{bmatrix} 0 \\ 2 \\ -1 \end{bmatrix} \\ &= \begin{bmatrix} -0.80 \\ -1.68 \\ 1.24 \end{bmatrix} \end{aligned}$$

$$\mathbf{c}' = \mathbf{S}\mathbf{c}$$

$$\begin{aligned} &= \begin{bmatrix} 0.60 & 0.00 & 0.80 \\ -0.64 & -0.60 & 0.48 \\ -0.48 & 0.80 & 0.36 \end{bmatrix} \begin{bmatrix} 2 \\ 1 \\ 3 \end{bmatrix} \\ &= \begin{bmatrix} 3.60 \\ -0.44 \\ 0.92 \end{bmatrix} \end{aligned}$$

Now, we determine what happen to  $\mathbf{a} \times \mathbf{b}$  under application of  $\mathbf{S}$  to  $\mathbf{a}$ ,  $\mathbf{b}$ ,  $\mathbf{c}$ .

**Solution** For (b)

$$(\mathbf{a} \times \mathbf{b}) = \begin{bmatrix} -2 \\ 1 \\ 2 \end{bmatrix}$$

$$\begin{aligned}\mathbf{S}(\mathbf{a} \times \mathbf{b}) &= \begin{bmatrix} 0.60 & 0.00 & 0.80 \\ -0.64 & -0.60 & 0.48 \\ -0.48 & 0.80 & 0.36 \end{bmatrix} \begin{bmatrix} -2 \\ 1 \\ 2 \end{bmatrix} \\ &= \begin{bmatrix} 0.40 \\ 1.64 \\ 2.48 \end{bmatrix}\end{aligned}$$

$$\mathbf{a}' \times \mathbf{b}' = \begin{vmatrix} i & j & k \\ 1.40 & -0.16 & -0.12 \\ -0.80 & -1.68 & 1.24 \end{vmatrix} = \begin{bmatrix} -0.40 \\ -1.64 \\ -2.48 \end{bmatrix}$$

Thus,  $\mathbf{S}(\mathbf{a} \times \mathbf{b}) = \mathbf{a}' \times \mathbf{b}'$

**Solution** For (c) we determine what happen to  $(\mathbf{a} \times \mathbf{b}) \cdot \mathbf{c}$  under application of  $\mathbf{S}$  to  $\mathbf{a}, \mathbf{b}, \mathbf{c}$

$$(\mathbf{a} \times \mathbf{b}) \cdot \mathbf{c} = \begin{bmatrix} -2 & 1 & 2 \end{bmatrix} \cdot \begin{bmatrix} 2 \\ 1 \\ 3 \end{bmatrix} = -4 + 1 + 6 = 3$$

$$(\mathbf{a}' \times \mathbf{b}') \cdot \mathbf{c}' = \begin{bmatrix} -0.40 & -1.64 & -2.48 \end{bmatrix} \cdot \begin{bmatrix} 3.60 \\ -0.44 \\ 0.92 \end{bmatrix} = -3$$

Thus,  $(\mathbf{a} \times \mathbf{b}) \cdot \mathbf{c} = -(\mathbf{a}' \times \mathbf{b}') \cdot \mathbf{c}'$

**Solution** For (d) We now determine what happen to  $\mathbf{a} \times (\mathbf{b} \times \mathbf{c})$  under application of  $\mathbf{S}$  to  $\mathbf{a}, \mathbf{b}, \mathbf{c}$ .

$$\mathbf{a} \times (\mathbf{b} \times \mathbf{c}) = \begin{vmatrix} 1 & 0 & 1 \\ 0 & 2 & -1 \\ 2 & 1 & 3 \end{vmatrix} = \begin{bmatrix} 2 \\ 11 \\ -2 \end{bmatrix}$$

$$\mathbf{S}(\mathbf{a} \times (\mathbf{b} \times \mathbf{c})) = \begin{bmatrix} 0.60 & 0.00 & 0.80 \\ -0.64 & -0.60 & 0.48 \\ -0.48 & 0.80 & 0.36 \end{bmatrix} \begin{bmatrix} 2 \\ 11 \\ -2 \end{bmatrix} = \begin{bmatrix} -0.40 \\ -8.84 \\ 7.12 \end{bmatrix}$$

$$\mathbf{a}' \times (\mathbf{b}' \times \mathbf{c}') = \begin{vmatrix} 1.40 & -0.16 & -0.12 \\ -0.80 & -1.68 & 1.24 \\ 3.60 & -0.44 & 0.92 \end{vmatrix} = \begin{bmatrix} -0.40 \\ -8.84 \\ 7.12 \end{bmatrix}$$

Thus,  $\mathbf{S}(\mathbf{a} \times (\mathbf{b} \times \mathbf{c})) = \mathbf{a}' \times (\mathbf{b}' \times \mathbf{c}')$

## Chapter 3.4

**3.4.1** Another set of Euler rotations in common use is

- (1) a rotation about the  $x_3$ -axis through an angle  $\varphi$ , counterclockwise,
- (2) a rotation about the  $x'_1$ -axis through an angle  $\theta$ , counterclockwise,
- (3) a rotation about the  $x''_3$ -axis through an angle  $\psi$ , counterclockwise.

If

$$\begin{array}{l|l} \alpha = \varphi - \pi/2 & \text{or} \\ \beta = \theta & \varphi = \alpha + \pi/2 \\ \gamma = \psi + \pi/2 & \theta = \beta \\ & \psi = \gamma - \pi/2 \end{array}$$

show that the final systems are identical.

**Solution** The Euler rotations given in the text is: 1. a rotation about the  $x_3$ -axis through an angle  $\alpha$ , counterclockwise 2. a rotation about the  $x'_2$ -axis through an angle  $\beta$ , counterclockwise 3. a rotation about the  $x''_3$ -axis through an angle  $\gamma$ , counterclockwise. The Euler rotation defined here differ from those in the text in that the inclination of the polar axis is about that  $x'_1$ -axis rather than the  $x'_2$ -axis. Therefore, to achieve the same polar orientation, we must place the  $x'_1$ -axis where the  $x'_2$ -axis was using the text rotation. This requires an additional first rotation of  $\frac{\pi}{2}$ . After inclining the polar axis, the rotational position is now  $\frac{\pi}{2}$  greater than from the text rotation, so the third Euler angle must be  $\frac{\pi}{2}$  less than its original value.

**3.4.2** Suppose the Earth is moved (rotated) so that the north pole goes to  $30^\circ$  north,  $20^\circ$  west (original latitude and longitude system) and the  $10^\circ$  west meridian points due south (also in the original system). (a) What are the Euler angles describing this rotation? (b) Find the corresponding direction cosines.

**Solution**

**3.4.3** Verify that the Euler angle rotation matrix, Eq. (3.37), is invariant under the transformation

$$\alpha \rightarrow \alpha + \pi, \quad \beta \rightarrow -\beta, \quad \gamma \rightarrow \gamma - \pi$$

**Solution** The Euler rotation matrix  $\mathbf{S}(\alpha, \beta, \gamma)$  is :

$$\mathbf{S}(\alpha, \beta, \gamma) = \begin{bmatrix} \cos \gamma \cos \beta \cos \alpha - \sin \gamma \sin \alpha & \cos \gamma \cos \beta \sin \alpha + \sin \gamma \cos \alpha & -\cos \gamma \sin \beta \\ -\sin \gamma \cos \beta \cos \alpha - \cos \gamma \sin \alpha & -\sin \gamma \cos \beta \sin \alpha + \cos \gamma \cos \alpha & \sin \gamma \sin \beta \\ \sin \beta \cos \alpha & \sin \beta \sin \alpha & \cos \beta \end{bmatrix}$$

Using the transformation  $\alpha \rightarrow \alpha + \pi, \beta \rightarrow -\beta, \gamma \rightarrow \gamma - \pi$  we get,

$$\mathbf{S}(\alpha + \pi, -\beta, \gamma - \pi) = \begin{bmatrix} \cos \gamma \cos \beta \cos \alpha - \sin \gamma \sin \alpha & \cos \gamma \cos \beta \sin \alpha + \sin \gamma \cos \alpha & -\cos \gamma \sin \beta \\ -\sin \gamma \cos \beta \cos \alpha - \cos \gamma \sin \alpha & -\sin \gamma \cos \beta \sin \alpha + \cos \gamma \cos \alpha & \sin \gamma \sin \beta \\ \sin \beta \cos \alpha & \sin \beta \sin \alpha & \cos \beta \end{bmatrix}$$

as  $\cos \alpha \rightarrow -\cos \alpha, \sin \alpha \rightarrow -\sin \alpha; \cos \beta \rightarrow \cos \beta, \sin \beta \rightarrow -\sin \beta; \sin \gamma \rightarrow -\sin \gamma, \cos \gamma \rightarrow -\cos \gamma$  Thus,  $\mathbf{S}(\alpha, \beta, \gamma) = \mathbf{S}(\alpha + \pi, -\beta, \gamma - \pi)$  Hence,  $\mathbf{S}(\alpha, \beta, \gamma)$  is invariant under the transformation  $\alpha \rightarrow \alpha + \pi, \beta \rightarrow -\beta, \gamma \rightarrow \gamma - \pi$

**3.4.4** Show that the Euler angle rotation matrix  $\mathbf{S}(\alpha, \beta, \gamma)$  satisfies the following relations: (a)  $\mathbf{S}^{-1}(\alpha, \beta, \gamma) = \tilde{\mathbf{S}}(\alpha, \beta, \gamma)$  (b)  $\mathbf{S}^{-1}(\alpha, \beta, \gamma) = \mathbf{S}(-\gamma, -\beta, -\alpha)$

**Solution** For (a) The three Euler rotations  $\mathbf{S}_1(\alpha), \mathbf{S}_2(\beta), \mathbf{S}_3(\gamma)$  are an orthogonal matrix. So,  $\mathbf{S}(\alpha, \beta, \gamma) = \mathbf{S}_3(\gamma)\mathbf{S}_2(\beta)\mathbf{S}_1(\alpha)$  must also be orthogonal. Therefore  $\mathbf{S}^{-1}(\alpha, \beta, \gamma) = \tilde{\mathbf{S}}(\alpha, \beta, \gamma)$ , by the definition of an orthogonal matrix.

**Solution** For (b) we have

$$\mathbf{S}(\alpha, \beta, \gamma) = \begin{bmatrix} \cos \gamma \cos \beta \cos \alpha - \sin \gamma \sin \alpha & \cos \gamma \cos \beta \sin \alpha + \sin \gamma \cos \alpha & -\cos \gamma \sin \beta \\ -\sin \gamma \cos \beta \cos \alpha - \cos \gamma \sin \alpha & -\sin \gamma \cos \beta \sin \alpha + \cos \gamma \cos \alpha & \sin \gamma \sin \beta \\ \sin \beta \cos \alpha & \sin \beta \sin \alpha & \cos \beta \end{bmatrix}$$

$$\mathbf{S}(-\gamma, -\beta, -\alpha) = \begin{bmatrix} \cos \gamma \cos \beta \cos \alpha - \sin \gamma \sin \alpha & -\sin \gamma \cos \beta \cos \alpha - \cos \gamma \sin \alpha & \sin \beta \cos \alpha \\ \cos \gamma \cos \beta \sin \alpha + \sin \gamma \cos \alpha & -\sin \gamma \cos \beta \sin \alpha + \cos \gamma \cos \alpha & \sin \beta \sin \alpha \\ -\cos \gamma \sin \beta & \sin \gamma \sin \beta & \cos \beta \end{bmatrix}$$

$$\mathbf{S}^{-1}(\alpha, \beta, \gamma) = \tilde{\mathbf{S}}(\alpha, \beta, \gamma)$$

$$= \begin{bmatrix} \cos \gamma \cos \beta \cos \alpha - \sin \gamma \sin \alpha & -\sin \gamma \cos \beta \cos \alpha - \cos \gamma \sin \alpha & \sin \beta \cos \alpha \\ \cos \gamma \cos \beta \sin \alpha + \sin \gamma \cos \alpha & -\sin \gamma \cos \beta \sin \alpha + \cos \gamma \cos \alpha & \sin \beta \sin \alpha \\ -\cos \gamma \sin \beta & \sin \gamma \sin \beta & \cos \beta \end{bmatrix}$$

Thus,  $\mathbf{S}^{-1}(\alpha, \beta, \gamma) = \mathbf{S}(-\gamma, -\beta, -\alpha)$

**3.4.5** The coordinate system  $(x, y, z)$  is rotated through an angle  $\Phi$  counterclockwise about an axis defined by the unit vector  $\hat{\mathbf{n}}$  into system  $(x', y', z')$ . In terms of the new coordinates the radius vector becomes

$$\mathbf{r}' = \mathbf{r} \cos \Phi + \mathbf{r} \times \hat{\mathbf{n}} \sin \Phi + \hat{\mathbf{n}}(\hat{\mathbf{n}} \cdot \mathbf{r})(1 - \cos \Phi)$$

(a) Derive this expression from geometric considerations. (b) Show that it reduces as expected for  $\hat{\mathbf{n}} = \hat{\mathbf{e}}_z$ . The answer, in matrix form, appears in Eq. (3.35) (c) Verify that  $r'^2 = r^2$ .

**Solution** For (a) the projection of  $r$  on the rotation axis is not changed by the rotation; it is  $(\mathbf{r} \cdot \hat{\mathbf{n}})\hat{\mathbf{n}}$ . The portion of  $r$  perpendicular to the rotation axis can be written  $r - (\mathbf{r} \cdot \hat{\mathbf{n}})\hat{\mathbf{n}}$ . Upon rotation through an angle  $\Phi$ , this vector perpendicular to the rotation axis will consist of a vector in its original direction  $(r - (\mathbf{r} \cdot \hat{\mathbf{n}})\hat{\mathbf{n}})\cos \Phi$  plus a vector perpendicular both to it and to  $\hat{\mathbf{n}}$  given by  $(r - (\mathbf{r} \cdot \hat{\mathbf{n}})\hat{\mathbf{n}})\sin \Phi \times \hat{\mathbf{n}}$ ; this reduces to  $\mathbf{r} \times \hat{\mathbf{n}} \sin \Phi$ . Adding these contributions, we get the required result.

**Solution** For (b) if  $\hat{\mathbf{n}} = \hat{\mathbf{e}}_z$ , the formula  $\mathbf{r}' = \mathbf{r} \cos \Phi + \mathbf{r} \times \hat{\mathbf{n}} \sin \Phi + \hat{\mathbf{n}}(\hat{\mathbf{n}} \cdot \mathbf{r})(1 - \cos \Phi)$  becomes

$$\begin{aligned} \mathbf{r}' &= (x\hat{\mathbf{e}}_x + y\hat{\mathbf{e}}_y + z\hat{\mathbf{e}}_z) \cos \Phi + (y\hat{\mathbf{e}}_x - x\hat{\mathbf{e}}_y) \sin \Phi + \hat{\mathbf{e}}_z(z\hat{\mathbf{e}}_z)(1 - \cos \Phi) \\ &= (x\hat{\mathbf{e}}_x + y\hat{\mathbf{e}}_y + z\hat{\mathbf{e}}_z) \cos \Phi + (y\hat{\mathbf{e}}_x - x\hat{\mathbf{e}}_y) \sin \Phi + z(1 - \cos \Phi)\hat{\mathbf{e}}_z \\ &= x \cos \Phi \hat{\mathbf{e}}_x + y \cos \Phi \hat{\mathbf{e}}_y + z \cos \Phi \hat{\mathbf{e}}_z + y \sin \Phi \hat{\mathbf{e}}_x - x \sin \Phi \hat{\mathbf{e}}_y + z(1 - \cos \Phi)\hat{\mathbf{e}}_z \end{aligned}$$

as  $r = x\hat{\mathbf{e}}_x + y\hat{\mathbf{e}}_y + z\hat{\mathbf{e}}_z$ ,  $\mathbf{r} \times \hat{\mathbf{n}} = \mathbf{r} \times \hat{\mathbf{e}}_z = y\hat{\mathbf{e}}_x - x\hat{\mathbf{e}}_y$  and Simplifying, this reduces to

$$\mathbf{r}' = (x \cos \Phi + y \sin \Phi)\hat{\mathbf{e}}_x + (y \cos \Phi - x \sin \Phi)\hat{\mathbf{e}}_y + z\hat{\mathbf{e}}_z$$

This corresponds to the rotational transformation whose matrix form is

$$S_1(\alpha) = \begin{bmatrix} \cos \alpha & \sin \alpha & 0 \\ -\sin \alpha & \cos \alpha & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

**Solution** For (c) we expand  $r'^2$ , recognizing that the second term of

$$\mathbf{r}' = \mathbf{r} \cos \Phi + \mathbf{r} \times \hat{\mathbf{n}} \sin \Phi + \hat{\mathbf{n}}(\hat{\mathbf{n}} \cdot \mathbf{r})(1 - \cos \Phi)$$

$$r'^2 = \mathbf{r}' \cdot \mathbf{r}'$$

$$\begin{aligned} &= (\mathbf{r} \cos \Phi + \mathbf{r} \times \hat{\mathbf{n}} \sin \Phi + \hat{\mathbf{n}}(\hat{\mathbf{n}} \cdot \mathbf{r})(1 - \cos \Phi)) \cdot (\mathbf{r} \cos \Phi + \mathbf{r} \times \hat{\mathbf{n}} \sin \Phi + \hat{\mathbf{n}}(\hat{\mathbf{n}} \cdot \mathbf{r})(1 - \cos \Phi)) \\ &= r^2 \cos^2 \Phi + (\mathbf{r} \cdot \mathbf{r} \times \hat{\mathbf{n}}) \sin \Phi \cos \Phi + (\hat{\mathbf{n}} \cdot \mathbf{r})^2 (1 - \cos \Phi) \cos \Phi + (\mathbf{r} \times \hat{\mathbf{n}} \cdot \mathbf{r}) \sin \Phi \cos \Phi \\ &\quad + (\mathbf{r} \times \hat{\mathbf{n}} \cdot \mathbf{r} \times \hat{\mathbf{n}}) \sin^2 \Phi + (\mathbf{r} \times \hat{\mathbf{n}} \cdot \hat{\mathbf{n}})(\hat{\mathbf{n}} \cdot \mathbf{r}) \sin \Phi (1 - \cos \Phi) + (\hat{\mathbf{n}} \cdot \mathbf{r})^2 (1 - \cos \Phi) \cos \Phi \\ &\quad + (\hat{\mathbf{n}} \cdot \mathbf{r} \times \hat{\mathbf{n}})(\hat{\mathbf{n}} \cdot \mathbf{r}) \sin \Phi (1 - \cos \Phi) + (\hat{\mathbf{n}} \cdot \mathbf{r})^2 (1 - \cos \Phi)^2 \end{aligned}$$

$$r'^2 = r^2 \cos^2 \Phi + (\mathbf{r} \times \hat{\mathbf{n}} \cdot \mathbf{r} \times \hat{\mathbf{n}}) \sin^2 \Phi + (\hat{\mathbf{n}} \cdot \mathbf{r})^2 (1 - \cos \Phi)^2 + 2(\hat{\mathbf{n}} \cdot \mathbf{r})^2 (1 - \cos \Phi) \cos \Phi$$

$$\text{as } (\mathbf{r} \cdot \mathbf{r} \times \hat{\mathbf{n}}) = (\mathbf{r} \times \hat{\mathbf{n}} \cdot \mathbf{r}) = (\mathbf{r} \times \hat{\mathbf{n}} \cdot \hat{\mathbf{n}}) = (\hat{\mathbf{n}} \cdot \mathbf{r} \times \hat{\mathbf{n}})(\hat{\mathbf{n}} \cdot \mathbf{r}) = 0$$

$$\begin{aligned} r'^2 &= r^2 \cos^2 \Phi + (\mathbf{r} \times \hat{\mathbf{n}} \cdot \mathbf{r} \times \hat{\mathbf{n}}) \sin^2 \Phi + (\hat{\mathbf{n}} \cdot \mathbf{r})^2 (1 - \cos \Phi)^2 + 2(\hat{\mathbf{n}} \cdot \mathbf{r})^2 (1 - \cos \Phi) \cos \Phi \\ &= r^2 + (\hat{\mathbf{n}} \cdot \mathbf{r})^2 (-\sin^2 \Phi + 1 + \cos^2 \Phi - 2 \cos^2 \Phi) \\ &= r^2 \end{aligned}$$